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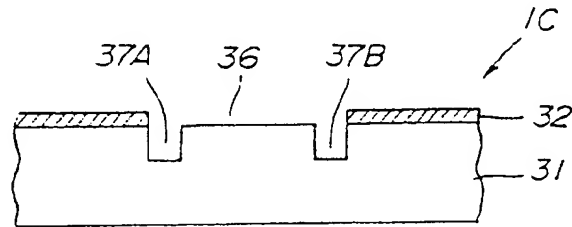
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(54) Mask, mask producing method and pattern forming method using mask.

(57) A mask for use in exposure of a semiconductor wafer includes transparent portions (2, 31, 51) for transmitting light used in the exposure, formed by a transparent layer and corresponding to first areas of the wafer, these being areas which are to be exposed, opaque portions (14, 32, 53) for masking the light, formed by an opaque layer and corresponding to second areas of the wafer adjacent to the first areas, and phase shift portions (3a, 37A, 37B, 41A, 41B) for shifting the phase of the light so as to improve the contrast between the first and second areas, formed by a phase shift layer (3a) formed over the transparent layer and the opaque layer. According to the invention, in at least one part of the mask the phase shift portions are formed only along

edges of the opaque portions (14, 32, 53) without extending between adjacent opaque portions. A method of producing such a mask, and a pattern forming method employing the mask, are also disclosed.

FIG. 46E



BACKGROUND OF THE INVENTION

The present invention generally relates to masks, mask producing methods and pattern forming methods using masks, and more particularly to a mask which uses a phase shift of light, a mask producing method for producing such a mask and a pattern forming method which uses such a mask.

When forming patterns of elements, circuits and the like on a semiconductor wafer in a production process of a semiconductor device, it is normal to employ a pattern transfer exposure which uses an ultraviolet light.

The pattern which is to be transferred onto the wafer is formed depending on the existence of a metal thin film which is provided on a glass substrate, where the metal thin film is opaque with respect to the light and the glass substrate is transparent with respect to the light. The pattern on the glass substrate to be transferred onto the wafer is called a mask when this pattern is identical to a chip pattern which is actually transferred onto the wafer. On the other hand, the pattern on the glass substrate is called an enlarged mask or a reticle when this pattern is enlarged compared to the chip pattern which is actually transferred onto the wafer. When using the mask, the pattern is transferred onto a resist layer on the wafer and exposed using a parallel ray. On the other hand, when using the reticle, the pattern is transferred onto the resist layer on the wafer and exposed using a reduction lens system which projects a reduced pattern on the resist layer.

In order to improve the resolution of the pattern which is transferred especially when the integration density of the integrated circuit is large and the pattern is fine, it is necessary to improve the contrast at an edge portion of the region which is exposed.

FIG.1 shows an example of a conventional mask which is made up of an opaque layer having a predetermined pattern and a transparent substrate. FIG.2 shows an example of an optical system for forming a pattern on the wafer using the mask shown in FIG.1.

In FIG.1, a mask 450 comprises a transparent substrate 452 and an opaque layer 451 which is made of a material such as chromium (Cr). The opaque layer 451 is formed to a predetermined pattern by lithography and etching processes.

In FIG.2, a light C which is emitted by an exposure apparatus (not shown) illuminates the mask 450. The light C cannot be transmitted through the opaque layer 451 but is transmitted through a portion of the transparent substrate 452 not provided with the opaque layer 451. The transmitted light passes through an imaging lens system 453 and exposes a resist material 455 which is coated on a wafer 454. For example, a resist OFPR manufactured by Tokyo Ooka Kogyo K. K. of Japan may be used as the resist material 455. As a result, a pattern identical to the pattern of the mask 450 is formed on the wafer 454 by an etching process.

When forming the pattern using an optical lens system, the exposure on the wafer 454 is made based solely on data related to the contrast which is determined by the existence of the opaque layer 451 on the transparent substrate 452. For this reason, there is a physical resolution limit to the pattern formation due to the wavelength of the light which is obtained via the optical lens system, and it is difficult to form a fine pattern depending on the wavelength of the light used for the exposure.

Conventionally, the photolithography process uses a reticle which is made by forming an opaque layer on a transparent substrate and patterning the opaque layer. For example, the opaque layer is made of Cr and the transparent substrate is made of a transparent material such as glass and quartz. FIGS.3A through 3D are diagrams for explaining such a conventional pattern forming method.

In FIG.3A, the optical system includes a light source 461, an illumination lens 462, and an imaging lens system 465. A reticle 464 is arranged between the illumination lens 462 and the imaging lens system 465. The light source 461 is made of a mercury lamp, an excimer laser or the like and is provided with a filter for emitting i-ray or g-ray. The light 463 from the light source 461 illuminates the reticle 464 via the illumination lens 462. For example, the partial coherency  $\sigma$  of the illumination lens 462 is 0.5. The reticle comprises a transparent substrate 468 and an opaque pattern 469 which is formed on the transparent substrate 468. For example, the transparent substrate 468 is made of glass and the opaque pattern 469 is made of Cr. The opaque pattern 469 on the reticle 464 is imaged on a photoresist layer 467 which is formed on a semiconductor substrate 466 via the imaging lens system 465. For example, the imaging lens system 465 has a numerical aperture (NA) of 0.50.

According to this pattern forming method, the resolution can be described by  $K1 \cdot \lambda / NA$ , where K1 denotes a process coefficient which is normally 0.6 to 0.8 and  $\lambda$  denotes the wavelength of the light. The wavelength  $\lambda$  of the light 463 is approximately 365 nm in the case of the i-ray which is emitted using the mercury lamp and is 248 nm or 198 nm when the excimer laser is used. The numerical aperture NA differs depending on the imaging lens system 465 which is used but is approximately 0.5, for example. In order to improve the resolution, it is necessary to set K1 or  $\lambda$  to a small value and set NA to a large value. However,

the values of  $K1$  and  $NA$  cannot be set freely. In addition, the value of  $\lambda$  is restricted by the light source 461 and the optical system used. The resolution is determined when the wavelength  $\lambda$  of the light used for the exposure, the numerical aperture  $NA$  and the process coefficient  $K1$  are determined, and it is impossible to image a pattern finer than the resolution.

5 The light 463 emitted from the light source 461 illuminates the entire surface of the reticle 464, and the portion of the light 463 which illuminates the opaque pattern 469 is stopped by the opaque pattern 469. For this reason, only the portion of the light 463 which illuminates the portion of the reticle 464 not provided with the opaque pattern 469 is transmitted through the reticle 464 and is imaged on the photoresist layer 467 via the imaging lens system 465. FIG.3B shows an electrical vector  $E$  of the light transmitted through  
10 the reticle 464, and FIG.3C shows a light intensity  $P$  of the light transmitted through the reticle 464. A pattern having a light intensity distribution proportional to the square of the amplitude of the light illuminating the photoresist layer 467 is formed on the photoresist layer 467 and the photoresist layer 467 is selectively exposed.

FIG.3D shows a portion of the reticle (opaque mask) 464 on an enlarged scale. A minimum width  $W$  of the pattern which can be exposed is restricted by the resolution which is determined by the imaging lens system 465.

Next, a description will be given of the light intensity distribution for cases where the pattern which is exposed is a line pattern which is finer than the resolution, by referring to FIGS.4A through 4D. In FIGS.4A through 4D, the wavelength  $\lambda$  of the light used is 365 nm, the numerical aperture  $NA$  is 0.50 and the partial  
20 coherency  $\sigma$  of the light is approximately 0.5.

FIG.4A shows the light intensity distribution for the case where the line pattern which is imaged has a width of 0.35  $\mu\text{m}$ . The light intensity approaches zero approximately at a center position (0.0) and gradually rises on both sides of the center position (0.0). The line width is approximately 1.0  $\mu\text{m}$  or greater at a position where the light intensity is a maximum. When the photoresist layer is developed using a position  
25 where the light intensity is approximately 0.2 as a developing threshold, it is possible to develop a pattern which has a designed width in the order of 0.35  $\mu\text{m}$ .

FIG.4B shows the light intensity distribution for the case where the line pattern which is imaged has a width of 0.30  $\mu\text{m}$ . A minimum of the light intensity at the center position (0.0) is increased compared to the light intensity distribution shown in FIG.4A. The width of the light intensity distribution itself shown in FIG.4B  
30 is not much different from that of FIG.4A.

FIGS.4C and 4D respectively show the light intensity distributions for the cases where the line pattern which are imaged have widths of 0.25  $\mu\text{m}$  and 0.20  $\mu\text{m}$ . In each of FIGS.4C and 4D, the minimum of the light intensity at the center position (0.0) is increased compared to the light intensity distribution shown in FIG.4A, similarly to the case shown in FIG.4B. The width of the light intensity distribution itself shown in  
35 each of FIGS.4C and 4D is not much different from that of FIG.4A. In other words, even when the pattern width is reduced exceeding the resolution, the pattern width of the light intensity distribution which is obtained does not decrease and the minimum of the light intensity at the center position (0.0) increases. In these cases, it is impossible to reduce the line width which is exposed, and the black level is exposed as a gray level. For these reasons, it is impossible to form an image which is finer than the resolution.

40 On the other hand, a method of shifting the phase of the light which is transmitted through the mask and exposed on the wafer by  $180^\circ$  depending on the patterns of the mask is proposed in Marc D. Levenson, "Improving Resolution in Photolithography with a Phase-Shifting Mask", IEEE TRANSACTIONS ON ELECTRON DEVICES, Vol.ED-29, No.12, December 1982. According to this proposed method, the interference between the patterns is eliminated so as to improve the contrast on the wafer and improve the resolution of the exposure apparatus.

45 However, it is difficult to apply this proposed method to masks and reticles having fine patterns, and there is a problem in that it is troublesome to generate pattern data peculiar to the phase shift pattern. For this reason, there is a demand to realize a phase shift pattern which is easily applicable to masks and reticles having fine patterns and does not substantially increase the number of processes such as the  
50 generation of the pattern data.

The phase shift pattern of the phase-shifting mask which is used according to this proposed method is formed as follows. First, an auxiliary pattern is formed in a vicinity of a design pattern (white pattern) which is to be transferred onto the wafer, where the auxiliary pattern has a width smaller than that of the design pattern. Second, a phase shifter is formed on the auxiliary pattern. The phase shifter is an organic pattern  
55 made of a resist or the like which is formed by coating, exposure and developing processes, or an inorganic pattern which is formed by chemical vapor deposition and lithography processes. For example, a description will now be given of a method of forming a phase-shifting mask which uses a negative resist pattern as the phase shifter, by referring to FIGS.5A through 5D.

In FIG.5A, an opaque layer 552 is formed on a glass substrate 551. An aperture pattern, that is, a design pattern 553 comprising a transmission region, and fine patterns 554A and 554B are formed in the opaque layer 552 by a lithography using an electron beam exposure. For example, the design pattern 553 has a width in the order of 1.5  $\mu\text{m}$ , and the fine aperture patterns 554A and 554B have a width in the order of 0.5  $\mu\text{m}$ . The fine aperture patterns 554A and 554B are formed as auxiliary patterns in a region neighboring the design pattern and separated by a distance in the order of 0.5  $\mu\text{m}$ , for example.

Next, as shown in FIG.5B, a transparent conductor layer 555 for preventing charge up at the time of the electron beam exposure is formed on the surface of the glass substrate 551 including the inner sides of the aperture patterns 553, 554A and 554B.

Then, as shown in FIG.5C, a negative resist layer 656 is formed on the glass substrate 551 to a thickness such that the phase of the light which is transmitted through the negative resist layer 656 is shifted by 180°. A prebaking process is made if needed, and a phase shift pattern is formed on the fine patterns 554A and 554B by the electron beam exposure.

A thickness D of the negative resist layer 656 can be obtained from the following formula (1), where  $\lambda$  denotes the wavelength of the light used for the exposure and n denotes a refractive index of the shifter material.

$$D = \lambda/2(n - 1) \quad (1)$$

When using the i-ray having the wavelength of 365 nm for the exposure, the refractive index n of the negative resist layer 656 is approximately 1.6 and the thickness D becomes approximately 304  $\mu\text{m}$ .

Next, as shown in FIG.5D, a developing process is made to selectively form phase shift patterns 556A and 556B on the fine patterns 554A and 554B, respectively. The phase shift patterns 556A and 556B is made up of the negative resist layer 656 which has the thickness D.

FIG.6 shows a phase profile corresponding to the pattern position of the i-ray transmitted through the phase-shifting mask shown in FIG.5D when the i-ray is used for the exposure.

On the other hand, when a positive resist is used, a phase shift pattern 557 which is made up of the positive resist is selectively formed on the design pattern 535 as shown in FIG.7 by processes similar to those described in conjunction with FIGS.5A through 5D. In FIG.7, those parts which are essentially the same as those corresponding parts in FIGS.5A through 5D are designated by the same reference numerals, and a description thereof will be omitted.

FIG.8 shows a phase profile corresponding to the pattern position of the i-ray transmitted through the phase-shifting mask shown in FIG.7 when the i-ray is used for the exposure.

According to the phase-shifting mask shown in FIGS.5D and 7, the phase of the i-ray ( $i_a$  and  $i_c$ ) which is transmitted through the design pattern 553 and the phase of the i-ray ( $i_b$  and  $i_d$ ) which is transmitted through the fine patterns (auxiliary patterns) 554A and 554B differ by 180° as may be seen from FIGS.6 and 8. For this reason, the i-ray ( $i_a$  and  $i_c$ ) which is scattered in the horizontal direction from the region immediately below the design pattern is cancelled by the i-ray ( $i_b$  and  $i_d$ ) which is scattered in the horizontal direction from the region immediately below the auxiliary pattern, and the contrast at the ends of the exposure region is improved thereby improving the resolution.

The aperture width of the auxiliary pattern is made narrow to such an extent that the light used for the standard exposure is insufficient to expose the resist layer to the bottom portion thereof. Hence, the auxiliary pattern will not be transferred onto the wafer when the exposure is made using the phase-shifting mask.

For example, the methods described in conjunction with FIGS.5 through 8 are proposed in Japanese Laid-Open Patent Applications No.61-292643, No.62-67514 and No.62-18946.

However, the conventional masks suffer from the following disadvantages.

First, in the case of the mask which uses no phase shift, it is difficult to form a pattern which is narrower than the wavelength of the light due to the physical resolution limit of the optical system. When an attempt is made to realize a narrow line width, it is necessary to make a structural modification such as reducing the wavelength of the light and increasing the numerical aperture. Accordingly, it is impossible to form the fine patterns which are required in the future integrated circuits using the optical method.

Second, in the case of the mask which uses the phase shift, the pattern formation can only be applied to a pattern such as the so-called line-and-space pattern which has regularity, and the pattern formation cannot be applied to the production of integrated circuits having various patterns. In addition, it is impossible to form a fine pattern because an opaque layer must always be provided.

Third, in the case of the mask which uses the phase shift, the auxiliary pattern must be patterned by the exposure technique to a degree finer than the design pattern. For this reason, the fineness of the design

pattern must be restricted in order that the resolution limit of the auxiliary pattern is not exceeded.

Fourth, in the case of the mask which uses the phase shift, the number of steps required to generate the pattern data is large because it is necessary to generate in addition to the data related to the design pattern the pattern data related to the auxiliary pattern, the pattern data related to the phase shift and the like.

Fifth, in the case of the mask which uses the phase shift, it is difficult to control the quality and thickness of the phase shifter which affects the refractive index when an organic material such as a resist is used for the phase shifter. For this reason, it is difficult to form a uniform phase shift pattern which has an accurate phase shift quantity.

Sixth, in the case of the mask which uses the phase shift, the phase shifter is made of a material different from the glass substrate. Thus, a reflection occurs at the boundary of the phase shifter and the glass substrate thereby deteriorating the exposure efficiency.

#### SUMMARY OF THE INVENTION

Accordingly, it is a general object of the present invention to provide a novel and useful mask, a mask producing method and a pattern forming method in which the problems described above are eliminated.

Another and more specific object of the present invention is to provide a mask comprising a transparent layer which is transparent with respect to a light which is used for an exposure, and a mask pattern layer which is formed on the transparent layer. At least a portion of the mask pattern layer is made up solely of a phase shift layer for transmitting the light, so that a phase shift occurs between a phase of the light transmitted through the phase shift layer and a phase of the light transmitted through a portion of the mask having no phase shift layer. According to the mask of the present invention, it is possible to form narrow patterns having width which exceeds the conventional resolution limit by effectively utilizing the phase shift layer.

Still another object of the present invention is to provide a mask which has a mask pattern comprising a transparent layer which is transparent with respect to a light which is used for an exposure, an opaque layer which is formed on the transparent layer, and a phase shift region which is formed only in a vicinity of an edge portion of the opaque layer. At least a portion of the mask pattern is made up of the opaque layer and the phase shift region, so that a phase shift occurs between a phase of the light transmitted through the phase shift region and a phase of the light transmitted through a portion of the mask having no phase shift region.

A further object of the present invention is to provide a mask producing method comprising the steps of forming a resist pattern which is made of a resist material on a transparent layer which is transparent with respect to a light which is used for an exposure, forming a phase shift layer which transmits the light on the resist pattern to a predetermined thickness, so that a phase shift occurs between a phase of the light transmitted through the phase shift layer and a phase of the light transmitted through a portion of the mask having no phase shift layer, and removing the resist pattern.

Another object of the present invention is to provide a mask producing method comprising the steps of forming a stopper layer on a transparent layer which is transparent with respect to a light which is used for an exposure, forming a phase shift layer which transmits the light on the stopper layer to a predetermined thickness, so that a phase shift occurs between a phase of the light transmitted through the phase shift layer and a phase of the light transmitted through a portion of the mask having no phase shift layer, forming a resist pattern which is made of a resist material on the phase shift layer, and etching the phase shift layer using the stopper layer as an etching stopper and the resist pattern as an etching mask.

Still another object of the present invention is to provide a mask producing method comprising the steps of forming an opaque pattern layer on a transparent layer which is transparent with respect to a light which is used for an exposure, forming a resist pattern which is made of a resist material on the opaque pattern layer, forming a phase shift layer which transmits the light on the resist pattern layer to a predetermined thickness, so that a phase shift occurs between a phase of the light transmitted through the phase shift layer and a phase of the light transmitted through a portion of the mask having no phase shift layer, and removing the resist pattern layer so that the phase shift layer remains on the transparent layer and the opaque pattern layer only in a vicinity of an edge portion of the opaque pattern layer in at least one part of the mask.

A further object of the present invention is to provide a mask producing method comprising the steps of forming an opaque pattern layer on a transparent layer which is transparent with respect to a light which is used for an exposure, forming a stopper layer on the opaque pattern layer, forming a phase shift layer which transmits the light on the opaque pattern layer to a predetermined thickness, so that a phase shift

occurs between a phase of the light transmitted through the phase shift layer and a phase of the light transmitted through a portion of the mask having no phase shift layer, forming a resist pattern which is made of a resist material on the phase shift layer, and etching the phase shift layer using the stopper layer as an etching stopper and the resist pattern as an etching mask so that the phase shift layer remains on the stopper layer only in a vicinity of an edge portion of the opaque pattern layer in at least one part of the mask.

Another object of the present invention is to provide a mask producing method comprising the steps of forming an opaque pattern layer on a transparent layer which is transparent with respect to a light which is used for an exposure, forming a resist pattern which is made of a resist material on the opaque pattern layer, and forming a phase shift region in a vicinity of an edge portion of the opaque pattern layer in at least one part of the mask by etching the transparent layer to a predetermined thickness using the resist pattern as an etching mask, so that a phase shift occurs between a phase of the light transmitted through the phase shift region and a phase of the light transmitted through a portion of the mask having no phase shift region.

Still another object of the present invention is to provide a mask producing method comprising the steps of forming a phase shift layer, forming an opaque pattern layer on the phase shift layer which is transparent with respect to a light which is used for an exposure, etching the phase shift layer to a predetermined thickness in a vicinity of an edge portion of the opaque pattern layer using the opaque pattern as an etching mask to form a phase shift region in the vicinity of the edge portion of the opaque pattern layer, forming a resist pattern which is made of a resist material on a selected portion of the opaque pattern layer, and etching a remaining portion of the opaque pattern, so that a phase shift occurs between a phase of the light transmitted through the phase shift region and a phase of the light transmitted through a portion of the mask having no phase shift region.

A further object of the present invention is to provide a mask producing method comprising the steps of forming an opaque pattern layer on a transparent layer which is transparent with respect to a light which is used for an exposure, etching the transparent layer to a predetermined thickness in a vicinity of an edge portion of the opaque pattern layer using the opaque pattern as an etching mask to form a phase shift region in the vicinity of the edge portion of the opaque pattern layer, forming a resist pattern which is made of a resist material on a selected portion of the opaque pattern layer, and etching a remaining portion of the opaque pattern layer, so that a phase shift occurs between a phase of the light transmitted through the phase shift region and a phase of the light transmitted through a portion of the mask having no phase shift region.

Another object of the present invention is to provide a mask producing method comprising the steps of forming an opaque pattern layer on a top of a transparent layer which is transparent with respect to a light which is used for an exposure, etching the transparent layer using the opaque pattern as an etching mask, forming a resist layer which is made of a resist material on the opaque pattern layer, exposing the resist layer from a bottom of the transparent layer so as to develop the resist layer into a resist pattern, removing a portion of the opaque pattern layer by a side etching, and forming a phase shift region by removing the resist pattern in a vicinity of an edge portion of the opaque pattern layer, so that a phase shift occurs between a phase of the light transmitted through the phase shift region and a phase of the light transmitted through a portion of the mask having no phase shift region.

Still another object of the present invention is to provide a mask producing method comprising the steps of forming an opaque pattern layer on a top of a transparent layer which is transparent with respect to a light which is used for an exposure, etching the transparent layer using the opaque pattern as an etching mask, forming a resist layer which is made of a resist material on the opaque pattern layer, exposing the resist layer from a bottom of the transparent layer so as to develop the resist layer into a resist pattern and to expose a portion of the opaque pattern layer, and forming a phase shift region by removing the exposed portion of the opaque pattern layer in a vicinity of an edge portion of the opaque pattern layer, so that a phase shift occurs between a phase of the light transmitted through the phase shift region and a phase of the light transmitted through a portion of the mask having no phase shift region.

A further object of the present invention is to provide a pattern forming method comprising the steps of illuminating a mask by a light from a light source, imaging the light transmitted through the mask onto a photoresist layer which is formed on a wafer by use of a lens system so as to develop a pattern on the photoresist layer, and developing the pattern on the photoresist layer, where the mask comprises a transparent layer which is transparent with respect to the light from the light source and a mask pattern layer which is formed on the transparent layer, and at least a portion of the mask pattern layer is made up solely of a phase shift layer for transmitting the light, so that an interference occurs between the light transmitted through the phase shift layer and the light transmitted through a portion of the mask having no phase shift layer.

Another object of the present invention is to provide a pattern forming method comprising the steps of illuminating a mask by a light from a light source, imaging the light transmitted through the mask onto a photoresist layer which is formed on a wafer by use of a lens system so as to develop a pattern on the photoresist layer, and developing the pattern on the photoresist layer, where the mask has a mask pattern and comprises a transparent layer which is transparent with respect to the light, an opaque layer which is formed on the transparent layer, and a phase shift region which is formed in a vicinity of an edge portion of the opaque layer, and at least a portion of the mask pattern is made up of the opaque layer and the phase shift region, so that an interference occurs between the light transmitted through the phase shift region and the light transmitted through a portion of the mask having no phase shift region.

Other objects and further features of the present invention will be apparent from the following detailed description when read in conjunction with the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG.1 is a cross sectional view showing a conventional mask provided with an opaque layer;  
 FIG.2 generally shows an optical system which forms a pattern using the mask shown in FIG.1;  
 FIGS.3A through 3D are diagrams for explaining a conventional pattern forming method;  
 FIGS.4A through 4D show light intensity distributions of the prior art;  
 FIGS.5A through 5D are cross sectional views for explaining a method of producing a conventional mask which has a phase shift layer and uses a negative resist;  
 FIG.6 shows a phase profile of the light transmitted through the mask shown in FIG.5D;  
 FIG.7 is a cross sectional view for explaining a method of producing a conventional mask which has a phase shift layer and uses a positive resist;  
 FIG.8 shows a phase profile of the light transmitted through the mask shown in FIG.7;  
 FIG.9 is a cross sectional view showing a first embodiment of a mask according to the present invention;  
 FIGS.10A through 10C are diagrams for explaining the light intensity at one edge portion of a phase shift layer;  
 FIGS.11A through 11C are diagrams for explaining the light intensity at two edge portions of the phase shift layer;  
 FIG.12 generally shows an optical system which is used for the exposure of the first embodiment of the mask;  
 FIG.13 is a diagram for explaining a first embodiment of a pattern forming method according to the present invention;  
 FIGS.14A through 14E are cross sectional views for explaining a first embodiment of a mask producing method according to the present invention;  
 FIGS.15A through 15F are cross sectional views for explaining a second embodiment of the mask producing method according to the present invention;  
 FIG.16 is a plan view showing a mask pattern;  
 FIGS.17A and 17B are diagrams for explaining the light intensity distribution in FIG.16;  
 FIGS.18A through 18C are diagrams for explaining a second embodiment of the pattern forming method according to the present invention;  
 FIG.19 is a cross sectional view showing a second embodiment of the mask according to the present invention;  
 FIGS.20A and 20B are diagrams for explaining the light intensity at one edge portion of the phase shift layer;  
 FIGS.21A and 21B are diagrams for explaining the light intensity at two edge portions of the phase shift layer;  
 FIG.22 is a diagram for explaining a third embodiment of the pattern forming method according to the present invention;  
 FIGS.23A and 23B are diagrams for explaining a pattern in FIG.19;  
 FIGS.24A and 24B are diagrams for explaining the light intensity distribution in FIG.23;  
 FIG.25 is a diagram for explaining the second embodiment of the mask applied to the line-and-space pattern;  
 FIGS.26A through 26D are diagrams for explaining the light intensity distribution for different dimension conversion quantities and widths of the phase shift layer;  
 FIG.27 is a diagram for explaining the conventional light intensity distribution in correspondence with FIG.25;



FIGS.28A through 28F are diagrams for explaining the light intensity distribution for the case where a KrF excimer laser is used in FIG.25;  
 FIGS.29A and 29B are diagrams showing a portion of FIG.19;  
 FIGS.30A and 30B are diagrams for explaining the light intensity distribution in FIG.23;  
 5 FIGS.31A and 31B are diagrams for explaining the formation of a black pattern on a white background;  
 FIGS.32A and 32B are diagrams for explaining the light intensity distribution in FIGS.31A and 31B;  
 FIGS.33A and 33B are diagrams for explaining the case where the second embodiment of the mask is applied to the formation of an integrated circuit pattern;  
 FIGS.34A through 34C are diagrams showing a portion of the pattern shown in FIG.19;  
 10 FIGS.35A and 35B are diagrams for explaining the light intensity distribution when a pattern width  $h = 0.3 \mu\text{m}$ ;  
 FIGS.36 through 41 respectively are diagrams for explaining the light intensity distributions when the pattern width  $h = 0.4, 0.5, 0.6, 0.7, 0.8$  and  $1.0 \mu\text{m}$ ;  
 FIGS.42A and 42B are diagrams for explaining the case where the second embodiment of the mask is applied to the formation of a contact hole pattern;  
 15 FIGS.43A and 43B are diagrams for explaining the light intensity distribution in FIGS.42A and 42B;  
 FIGS.44A through 44F are cross sectional views for explaining a third embodiment of the mask producing method according to the present invention;  
 FIGS.45A through 45E are cross sectional views for explaining a fourth embodiment of the mask producing method according to the present invention;  
 20 FIGS.46A through 46E are cross sectional views for explaining a fifth embodiment of the mask producing method according to the present invention;  
 FIG.47 shows a phase profile of the light transmitted through the mask shown in FIG.46E;  
 FIGS.48A through 48C are cross sectional views for explaining a sixth embodiment of the mask producing method according to the present invention;  
 25 FIG.49 shows a phase profile of the light transmitted through the mask shown in FIG.48C;  
 FIGS.50A through 50H are diagrams for explaining a seventh embodiment of the mask producing method according to the present invention;  
 FIGS.51A through 51G are diagrams for explaining an eighth embodiment of the mask producing method according to the present invention;  
 30 FIGS.52A through 52F are diagrams for explaining a ninth embodiment of the mask producing method according to the present invention;  
 FIGS.53A through 53F are diagrams for explaining a tenth embodiment of the mask producing method according to the present invention;  
 35 FIGS.54A through 54E are diagrams for explaining an eleventh embodiment of the mask producing method according to the present invention;  
 FIGS.55A through 55C are diagrams for explaining the pattern forming method using the mask;  
 FIGS.56A and 56B show light intensity distributions for explaining the imaging using the edge portion of the phase shift layer;  
 40 FIGS.57A and 57B are diagrams for explaining the formation of a loop shaped pattern in a fourth embodiment of the pattern forming method according to the present invention;  
 FIGS.58A and 58B are diagrams for explaining the formation of an open shaped pattern in the fourth embodiment of the pattern forming method according to the present invention;  
 FIGS.59A and 59B are diagrams for explaining the formation of a point pattern in the fourth embodiment of the pattern forming method according to the present invention;  
 45 FIGS.60A through 60C are diagrams for explaining the formation of an intersecting line pattern in the fourth embodiment of the pattern forming method according to the present invention;  
 FIGS.61A and 61B are diagrams for explaining the formation of a T-shaped pattern in the fourth embodiment of the pattern forming method according to the present invention;  
 50 FIGS.62A through 62D are diagrams for explaining the formation of an interconnection pattern in the fourth embodiment of the pattern forming method according to the present invention;  
 FIGS.63A through 63C are diagrams for explaining the intersecting pattern;  
 FIGS.64A through 64C are diagrams for explaining the interconnection pattern;  
 FIGS.65A through 65C are diagrams for explaining the interconnection pattern;  
 55 FIGS.66A through 66C are diagrams for explaining the oval pattern;  
 FIGS.67A and 67B are diagrams for explaining the line-and-space pattern;  
 FIGS.68A and 68B are diagrams for explaining a mixed pattern of various sizes;

FIG.69 is a cross sectional view showing a sixth embodiment of the mask according to the present invention;

FIGS.70A through 70E, FIGS.71A through 71D and FIGS.72A through 72D are diagrams for explaining the light intensity distribution for phase shift layers having different thicknesses;

5 FIG.73 is a diagram for explaining a fifth embodiment of the pattern forming method according to the present invention; and

FIGS.74A, 74B, 75A, 75B, 76A, 76B, 77A and 77B are diagrams showing examples of the patterns formed according to the present invention.

## 10 DESCRIPTION OF THE PREFERRED EMBODIMENTS

A description will be given of a first embodiment of a mask according to the present invention, by referring to FIG.9. In FIG.9, a mask 1 comprises a transparent substrate 2 which is transparent with respect to a light L which is used for the exposure, and a mask pattern layer 5 which is formed on the transparent substrate 2. At least one portion of the mask pattern layer 5 is made up solely of a phase shift layer 3a. The light L can be transmitted through the phase shift layer 3a.

The phase of the light which is transmitted through the phase shift layer 3a is shifted from the phase of the light which is transmitted through only the transparent substrate 2. Accordingly, an interference occurs and the light intensity decreases at the boundary of the light which is transmitted through only the transparent substrate 2 and the light which is transmitted through the phase shift layer 3a. For this reason, it is possible to form on a wafer (not shown) an interference pattern which is smaller than the wavelength of the light L which is used for the exposure. In addition, it is possible to adjust the phase shift quantity of the light and improve the resolution of the exposure pattern by adjusting the thickness of the mask pattern layer 5.

25 FIGS.10A through 10C are diagrams for explaining the light intensity at one edge portion of the phase shift layer 3a of the mask 1. In FIG.10A, the phase of the light transmitted through the transparent substrate 2 and the phase shift layer 3a is shifted by approximately  $180^\circ$  with respect to the light transmitted through only the transparent substrate 2. Hence, an electrical vector E and a light intensity P of the light transmitted through the mask 1 respectively become as shown in FIGS.10B and 10C. As may be seen from FIG.10C, it is possible to expose a line pattern by using the light intensity change at the edge portion of the phase shift layer 3a.

FIGS.11A through 11C are diagrams for explaining the light intensity at two edge portions of the phase shift layer 3a of the mask 1. In FIGS.11A through 11C, those parts which are the same as those corresponding parts in FIGS.10A through 10C are designated by the same reference numerals, and a description thereof will be omitted. In this case, the light intensity P of the light transmitted through the mask 1 becomes as shown in FIG.11C when a width W of the phase shift layer 3a is sufficiently small. Thus, it is possible to control the width of the line pattern by controlling the width W.

FIG.12 generally shows an optical system which is used for the exposure using the mask 1. For example, a light source 6 is made up of a mercury lamp and the mercury lamp is provided with a filter (not shown) for passing only the i-ray which has the wavelength of 365 nm. The light from the light source 6 passes through an illumination lens system 8 and reaches the mask 1 as the light L. The mask 1 is positioned at the focal distance of the lens system 8. The partial coherency  $\sigma$  of the light L is 0.5 in this embodiment, but the partial coherency  $\sigma$  may be selected within a range such that  $0.3 \leq \sigma \leq 0.7$ .

The light transmitted through the mask 1 is imaged on a wafer 11 which is coated with a photoresist layer 10 via an imaging lens system 9. The imaging lens system 9 includes a 1/5 reduction lens and has a numerical aperture NA of 0.5. The wafer 11 is maintained flat by a chuck (not shown).

Next, a description will be given of a first embodiment of a pattern forming method according to the present invention, by referring to FIG.13 which shows the exposure state in FIG.12. The light which passes through the illumination lens system 8 shown in FIG.12 is transmitted through the mask 1, and the light which is transmitted through the mask 1 can be divided into a light 7a which is transmitted through the mask pattern layer 5 of the mask and a light 7b which is transmitted through a portion of the mask 1 not provided with the mask pattern layer 5. The phase of the light 7a differs by  $180^\circ$  with respect to the phase of the light 7b.

The lights 7a and 7b is imaged on the photoresist layer 10 on the wafer 11 via the imaging lens system 9. A sharp light intensity change occurs at a portion which corresponds to the edge portion of the phase shift layer 3a due to the interference. Hence, it is possible to form on the wafer 11 a pattern which is smaller than the wavelength of the light used for the exposure.

Next, a description will be given of first and second embodiments of a mask producing method according to the present invention, by referring to FIGS. 14 and 15. In FIGS. 14 and 15, those parts which are essentially the same as those corresponding parts in FIG. 9 are designated by the same reference numerals.

In FIG. 14A, the transparent substrate 2 is made of a material such as quartz and glass which transmits the i-ray. A resist material 3 is formed on the transparent substrate 2 as shown in FIG. 14B. A resist such as an electron beam (EB) resist and a photoresist is used as the resist material 3. When the EB resist is used as the resist material 3, a resist pattern 4 shown in FIG. 14C is formed by drawing by the electron beam and carrying out a developing process. Then, a silicon oxide which constitutes the phase shift layer 3a is sputtered on the surface of the resist pattern 4 as shown in FIG. 14D to a thickness of 0.388  $\mu\text{m}$ . Thereafter, the EB resist is removed by using a resist removal agent so that the mask pattern layer 5 of the phase shift layer (silicon oxide layer) 3a is formed on the transparent substrate 2 as shown in FIG. 14E.

On the other hand, in the embodiment shown in FIGS. 15A through 15F, the transparent substrate 2 shown in FIG. 15A is the same as that shown in FIG. 14A but an aluminum oxide thin film 12 is formed on the transparent substrate 2 as shown in FIG. 15B. As shown in FIG. 15C, a silicon oxide which constitutes the phase shift layer 3a is sputtered on the thin film 12 to a thickness of 0.388  $\mu\text{m}$ . Furthermore, the resist material 3 is formed on the phase shift layer 3a as shown in FIG. 15D. A resist pattern 4 shown in FIG. 15E is formed by drawing by the electron beam and carrying out a developing process. Thereafter, a plasma etching or a reactive ion etching (RIE) is carried out on the phase shift layer 3a by using a  $\text{CF}_4$  gas. The resist material 3 is removed by the ashing of the oxygen plasma, and the mask pattern 5 of the phase shift layer (silicon oxide layer) 3a is formed as shown in FIG. 15F. Because the thin film 12 is not etched by the  $\text{CF}_4$  gas, the thin film 12 acts as an etching stopper. Thus, it is possible to obtain the mask pattern 5 which is made up of the phase shift layer 3a accurately having the thickness of 0.388  $\mu\text{m}$ .

The thickness of the phase shift layer 3a is set to 0.388  $\mu\text{m}$  for the purpose of shifting the phase of the i-ray by  $180^\circ$ , that is, inverting the phase. The phase shift quantity and the thickness of the phase shift layer 3a can be described by the following general formula (2), where n denotes the refractive index of the phase shift layer 3a,  $\lambda$  denotes the wavelength of the light L used, S denotes the (phase shift quantity)/ $2\pi$  - (or 1/2 when inverting the phase), and t denotes the thickness of the phase shift layer 3a.

$$(n \cdot t / \lambda) - (t / \lambda) = S \quad (2)$$

In the embodiments shown in FIGS. 14 and 15, the refractive index n of the phase shift layer 3a is 1.47, the wavelength  $\lambda$  of the light L used is 0.365 nm, and the phase shift quantity S is 1/2. Hence, the general formula (2) can be rewritten as the following formula (3).

$$(1.47t/0.365) - (t/0.365) = 1/2 \quad (3)$$

Therefore, the thickness t of the phase shift layer 3a is calculated as 0.388  $\mu\text{m}$  from the formula (3). The phase shift quantity S is set to 1/2 ( $180^\circ$ ) in these embodiments because  $180^\circ$  is an optimum phase shift quantity for forming the pattern by the interference.

FIG. 16 shows a plan view of the mask pattern 5 of the mask 1 which is produced in the above described manner. When forming a line-and-space pattern with the resolution limit of 0.35  $\mu\text{m}$  by use of a 1/5 reduction lens system, a light intensity shown in FIG. 17B can be obtained on the wafer 11 when a width b is set to 0.15  $\mu\text{m}$  (reticle size of 0.75  $\mu\text{m}$ ) and a width a of a region 13 having no phase shift layer 3a is set to 0.55  $\mu\text{m}$  (reticle size of 2.75  $\mu\text{m}$ ).

A comparison will now be made of FIGS. 17B and 17A. For the sake of convenience, it is assumed that the opaque layer 451 shown in FIG. 1 is made of Cr and has a thickness in the range of 50 to 80 nm and a width of 0.35  $\mu\text{m}$  (reticle size of 1.75  $\mu\text{m}$ ) for the conventional method. In addition, it is assumed that the interval of the opaque pattern is set to 0.35  $\mu\text{m}$  (reticle size of 1.75  $\mu\text{m}$ ) for the conventional method. As shown in FIG. 17A, the light intensity is approximately 50 % according to the conventional method, and it is evident that the contrast is poor. In this state, it is impossible to form a pattern on the photoresist layer 455 on the wafer 454 in FIG. 2. But on the other hand, in the above described embodiments, the light intensity is approximately 80 % on the wafer 11 as shown in FIG. 17B. Accordingly, the light intensity is greatly improved. In addition, the contrast (resolution) is greatly improved because there is no change at the dark portion.

Next, a description will be given of a second embodiment of the pattern forming method according to the present invention, by referring to FIG. 18. FIGS. 18A and 18B respectively are a plan view and a cross sectional view showing the mask 1 which is for forming a pattern on the wafer, where large and fine patterns coexist in the pattern. An opaque layer 14 which is made of a Cr layer having a thickness of 50 to 80 nm is

indicated by a hatched region. In addition, an exposed portion of the transparent substrate 2 is indicated by a white background. The exposed portion is divided into a large pattern region 15 and a fine pattern region 16. The phase shift layer 3a is formed within the line pattern region 16. The large pattern region 15 is patterned by the conventional method, while the line pattern region 16 is formed by use of the phase shift layer 3a. Large patterns and line patterns usually coexist in the integrated circuit. Hence, this embodiment is especially suited for patterning the integrated circuit. FIG.18C shows a pattern which is imaged on the wafer 11 by using the mask shown in FIGS.18A and 18B. According to this embodiment, it is possible to form the pattern in a small number of steps even when the pattern includes fine patterns, and it is possible to sufficiently improve the resolution.

Next, a description will be given of a second embodiment of the mask according to the present invention, by referring to FIG.19. A mask 1A shown in FIG.19 comprises the transparent substrate 2, an opaque layer 14 which is formed on the transparent substrate 2, and the phase shift layer 3a which is formed at the edge portion of the opaque layer 14. For example, the opaque layer 14 is made of Cr and is formed to a thickness of 50 to 80 nm. For the sake of convenience, it is assumed that a fine pattern is isolated on the left part of the transparent substrate 2 in FIG.19 and fine patterns are located adjacent to each other on the right part of the transparent substrate 2. In addition, a pattern 3b for forming a fine pattern is made up solely of the phase shift layer 3a. This pattern 3b is transferred onto the wafer 11 by the interference caused by the phase shifter, as will be described later in the specification. Distances  $a$ ,  $b$  and  $c$  shown in FIG.19 will also be described later in the specification.

FIGS.20A and 20B are diagrams for explaining the light intensity at the edge portion of the phase shift layer 3a of the mask 1A. In FIG.20A, the phase of the light transmitted through the transparent substrate 2 and the phase shift layer 3a is shifted by approximately  $180^\circ$  with respect to the light transmitted through only the transparent substrate 2. Hence, the light intensity  $P$  of the light transmitted through the mask 1A becomes as shown in FIG.20B. As may be seen from FIG.20B, it is possible to expose a line pattern by using the light intensity change at the edge portion of the phase shift layer 3a.

FIGS.21A and 21B are diagrams for explaining the light intensity at two edge portions of the phase shift layer 3a of the mask 1A. In FIGS.21A and 21B, those parts which are the same as those corresponding parts in FIGS.20A and 20B are designated by the same reference numerals, and a description thereof will be omitted. In this case, the light intensity  $P$  of the light transmitted through the mask 1A becomes as shown in FIG.21B. Thus, it is possible to control the width of the line pattern by controlling the width  $W$ .

Next, a description will be given of a third embodiment of the pattern forming method according to the present invention, by referring to FIG.22 which generally shows an optical system which uses the mask 1A for the exposure. In FIG.22, those parts which are essentially the same as those corresponding parts in FIG.13 are designated by the same reference numerals, and a description thereof will be omitted.

In FIG.22, the light  $L$  which originates from the light source 6 and reaches the mask 1A via the illumination lens system 8 cannot be transmitted through the opaque layer 14. The phase of the light 7a transmitted through the phase shift layer 3a is shifted and is inverted with respect to the phase of the light 7b which is transmitted through only the transparent substrate 2. The lights 7a and 7b are imaged on the photoresist layer 10 on the wafer 11 via the imaging lens system 9. In this case, the lights 7a and 7b mutually interfere and a sharp light intensity change occurs. Accordingly, it is possible to improve the contrast between the portion provided with no opaque layer 14 and the portion provided with the opaque layer 14. The conditions of the optical system shown in FIG.22 are the same as those of the optical system shown in FIG.13. Thus, the thickness of the phase shift layer 3a is set to  $0.388 \mu\text{m}$  and the phase shift quantity is set to  $180^\circ$  based on the formula (3).

Next, a description will be given of the effects obtained by forming the phase shift layer 3a at the edge portion of the opaque layer 14, by referring to FIGS.23 through 26.

FIG.23A shows a case where no phase shift layer 3a is provided at the edge portion of the opaque layer 14, and FIG.23B shows a case where the phase shift layer 3a is provided at the edge portion of the opaque layer 3a with a width  $b$  of  $0.15 \mu\text{m}$ . FIGS.24A and 24B respectively show the light intensity distributions for the cases shown in FIGS.23A and 23B. In the case shown in FIG.24B, it can be seen that the light intensity distribution changes sharply at the portion of the phase shift layer 3a in a vicinity of  $0.0 \mu\text{m}$  on the x-axis. In other words, it can be seen from FIG.24B that the capability of forming the fine pattern is large in this case. In this case, the boundary of the phase shift layer 3a and the exposed portion of the transparent substrate 2 is  $0.0 \mu\text{m}$  on the x-axis. Thus, when the boundary of the opaque layer 14 and the phase shift layer 3a is assumed to be  $-0.15 \mu\text{m}$  on the x-axis, the boundary between the black and white portions of the pattern becomes  $+0.1 \mu\text{m}$  from FIG.16B.

Therefore, when the light used for the exposure is the i-ray having the wavelength of 365 nm and the numerical aperture NA of the lens system is 0.5, it is possible to form the resist pattern to the designed

dimension when the exposed portion of the transparent substrate 2 is made  $0.2\text{ }\mu\text{m}$  ( $0.1\text{ }\mu\text{m}$  on each side) larger than the designed dimension and the phase shift layer 3a is formed with a width of  $0.15\text{ }\mu\text{m}$  on the periphery of the exposed portion of the transparent substrate 2. In the case where the mask 1A is a reticle which has the pattern with a dimension five times that of the resist pattern to be exposed on the wafer 11, it is possible to form the resist pattern to the designed dimension when the exposed portion of the transparent substrate 2 is made  $1.0\text{ }\mu\text{m}$  ( $0.5\text{ }\mu\text{m}$  on each side) larger than the designed dimension and the phase shift layer 3a is formed with a width of  $0.75\text{ }\mu\text{m}$  on the periphery of the exposed portion of the transparent substrate 2. In the description given hereunder, it is assumed for the sake of convenience that the reticle is made according to the same rule.

The above rule must be changed when the wavelength  $\lambda$  of the light or the numerical aperture NA of the lens system changes. In other words, it is necessary to change the dimension conversion quantity of the exposed portion of the transparent substrate 2 and the width of the phase shift layer 3a formed in the periphery of the edge portion of the opaque layer 14. For example, when a KrF laser is used as the light source which emits a light having a wave length of  $248\text{ nm}$  and the lens system used has a numerical aperture of  $0.48$ , it is possible to obtain an optimum effect when the exposed portion of the transparent substrate 2 is made  $0.13\text{ }\mu\text{m}$  ( $0.065\text{ }\mu\text{m}$  on each side) larger than the designed dimension and the phase shift layer 3a at the periphery of the edge portion of the opaque layer 14 is formed with a width of  $0.06\text{ }\mu\text{m}$ . In the case where the mask 1A is a reticle which has the pattern with a dimension five times that of the resist pattern to be exposed on the wafer 11, it is possible to obtain the optimum effect when the exposed portion of the transparent substrate 2 is made  $0.65\text{ }\mu\text{m}$  ( $0.325\text{ }\mu\text{m}$  on each side) larger than the designed dimension and the phase shift layer 3a is formed with a width of  $0.30\text{ }\mu\text{m}$  on the periphery of the exposed portion of the transparent substrate 2. When the white patterns close upon each other, the region of the opaque layer 14 disappears between the white patterns and the white patterns are separated solely by the phase shift layer 3a.

It is known from experience that the resolution is improved by  $20\%$  when the phase shift method is employed. Hence, the dimension conversion quantity at the exposed portion of the transparent substrate 2 and the width of the phase shift layer 3a can be obtained from experience. That is, when the i-ray is used for the exposure and the numerical aperture NA of the lens system is  $0.5$ , the resolution limit for the case where no phase shift is made can be described by  $0.6 \times (\lambda/NA)$  and the resolution limit for the case where the phase shift is made can be described by  $0.6 \times (\lambda/NA) \times 0.8$ . Therefore, the width of the phase shift layer 3a can be calculated as  $0.35\text{ }\mu\text{m}$  when numerical values are substituted.

FIG.25 shows a case where this embodiment is applied to the so-called line-and-space pattern. In FIG.25, the phase shift layer 3a is formed at the edge portion of the opaque layer 14, and the phase shift layer 3a is also formed between the four spaces in which the transparent substrate 2 is exposed.

FIGS.26A through 26D show the light intensity distributions of the line-and-space pattern with the resolution limit of  $0.35\text{ }\mu\text{m}$  when the phase shift is made when the dimension conversion quantity  $a$  at the exposed portion of the transparent substrate 2 and the width  $b$  of the phase shift layer 3a are varied. FIG.26A shows the light intensity distribution for the case where  $a = 0.45\text{ }\mu\text{m}$  and  $b = 0.25\text{ }\mu\text{m}$ . FIG.26B shows the light intensity distribution for the case where  $a = 0.50\text{ }\mu\text{m}$  and  $b = 0.20\text{ }\mu\text{m}$ . FIG.26C shows the light intensity distribution for the case where  $a = 0.55\text{ }\mu\text{m}$  and  $b = 0.15\text{ }\mu\text{m}$ . FIG.26D shows the light intensity distribution for the case where  $a = 0.60\text{ }\mu\text{m}$  and  $b = 0.10\text{ }\mu\text{m}$ . It is necessary that  $a + b = 0.70\text{ }\mu\text{m}$  in order that the line-and-space pattern is formed. As may be seen from FIGS.26A through 26D, the peak of the light intensity decreases when the width  $b$  of the phase shift layer 3a is large. In addition, when the width  $b$  of the phase shift layer 3a is small, the light intensity at the space portion becomes large and the contrast decreases. An optimum contrast is obtained when  $b = 0.15\text{ }\mu\text{m}$ , and  $a = 0.55\text{ }\mu\text{m}$  in this case. The boundary between the phase shift layer 3a and the exposed portion of the transparent substrate 2 is shifted so as to enlarge the exposed portion of the transparent substrate 2 by  $0.10\text{ }\mu\text{m}$  on each side from the designed dimension, and this case corresponds to the edge portion of the large pattern described above. The width  $b$  of the phase shift layer 3a must be set within  $30$  to  $60\%$  of the resolution limit, that is, within the range of  $0.144$  to  $0.228\text{ }\mu\text{m}$ .

A high contrast can be obtained especially when the width  $b$  of the phase shift layer 3a is set within  $40$  to  $50\%$  of the resolution limit.

FIG.27 shows the light intensity distribution of the conventional mask shown in FIG.1 for the case where the width of the exposed portion of the transparent substrate 452 is  $0.35\text{ }\mu\text{m}$  and the width of the opaque layer 451 is  $0.35\text{ }\mu\text{m}$ . In the case where the mask shown in FIG.27 is a reticle which has the pattern with a dimension five times that of the resist pattern to be exposed on the wafer, FIG.27 corresponds to the light intensity distribution of the conventional reticle for the case where the width of the exposed portion of the transparent substrate 452 is  $1.75$  and the width of the opaque layer 451 is  $1.75\text{ }\mu\text{m}$ . In FIG.27, the light

intensity is approximately 55 % while the light intensity is approximately 80 % in FIG.26C. Hence, it is readily seen that the contrast is greatly improved in this embodiment.

When the KrF excimer laser is used to emit a light having a wavelength of 248 nm and the lens system used has a numerical aperture NA of 0.48, the resolution limit is 0.25  $\mu\text{m}$  when the phase shift is made. FIGS.28B through 28F show the light intensity distributions of for this case when the dimension conversion quantity  $a$  at the exposed portion of the transparent substrate 2 and the width  $b$  of the phase shift layer 3a are varied. FIG.28A shows for comparison purposes the light intensity distribution for the case where no phase shift is made. FIG.28B shows the light intensity distribution for the case where  $a = 0.35 \mu\text{m}$  and  $b = 0.15 \mu\text{m}$ . FIG.28C shows the light intensity distribution for the case where  $a = 0.36 \mu\text{m}$  and  $b = 0.14 \mu\text{m}$ . FIG.28D shows the light intensity distribution for the case where  $a = 0.38 \mu\text{m}$  and  $b = 0.12 \mu\text{m}$ . FIG.28E shows the light intensity distribution for the case where  $a = 0.40 \mu\text{m}$  and  $b = 0.10 \mu\text{m}$ . FIG.28F shows the light intensity distribution for the case where  $a = 0.42 \mu\text{m}$  and  $b = 0.08 \mu\text{m}$ . An optimum contrast is obtained when  $b = 0.12 \mu\text{m}$  as may be seen from FIG.28D. The width  $b$  of the phase shift layer 3a must be set within 30 to 60 % of the resolution limit.

FIG.29A shows a portion of the mask 1A shown in FIG.19. In FIG.29A, the phase shift layer 3a is formed at both edge portions of the opaque layer 14, and the transparent substrate 2 is exposed between the phase shift layers 3a. On the other hand, FIG.29B shows a portion of the conventional mask 450 shown in FIG.1 for comparison purposes. In FIG.29B, the mask pattern made solely of the opaque layer 451 is formed on the transparent substrate 452.

When comparing FIGS.29A and 29B, it is assumed that the width  $a$  of the exposed portion of the transparent substrate 2 shown in FIG.29A is 0.55  $\mu\text{m}$  (reticle size of 2.75  $\mu\text{m}$ ), the width  $b$  of the phase shift layer 3a is 0.15  $\mu\text{m}$  (reticle size of 1.75  $\mu\text{m}$ ), and the width  $d$  of the exposed portion of the transparent substrate 452 shown in FIG.29B is 0.35  $\mu\text{m}$  (reticle size of 1.75  $\mu\text{m}$ ). FIGS.30A and 30B respectively show the light intensity distributions for the cases shown in FIGS.29A and 29B. As may be seen from FIG.30A, the light intensity is approximately 100 % in this embodiment while the light intensity is approximately 65 % in the conventional case, and it can be seen that the contrast is greatly improved according to this embodiment. Therefore, it is possible to obtain satisfactory results when the exposed portion of the transparent substrate 2 is formed larger than the designed pattern which is to be formed on the wafer and the phase shift layer 3a is formed on the peripheral portion of the exposed portion of the transparent substrate 2.

Next, a description will be given of a case where a black pattern is formed on a white background, by referring to FIGS.31A and 31B. FIG.31A shows a mask for forming a black pattern of 0.35  $\mu\text{m}$  using the phase shift. According to the rule described above, the mask pattern is made up solely of the phase shift layer 3a which has a width  $c$  of 0.15  $\mu\text{m}$  (reticle size of 0.75  $\mu\text{m}$ ). In this case, the light intensity of the pattern imaged on the wafer becomes as shown in FIG.32A. On the other hand, FIG.31B shows a mask for forming the black pattern of 0.35  $\mu\text{m}$  without the use of the phase shift. The mask shown in FIG.31B is made up of the opaque layer 14 having a width of 0.35  $\mu\text{m}$  (reticle size of 1.75  $\mu\text{m}$ ). In this case, the light intensity of the pattern imaged on the wafer becomes as shown in FIG.32B. As may be seen by comparing FIGS.32A and 32B, there is a sharp decrease in the light intensity when the phase shift is used, and the resolution of the black pattern is improved.

FIGS.33A and 33B show the case where this embodiment is applied to the formation of the integrated circuit pattern. FIG.33A is a plan view showing a portion of the mask 1A, and FIG.33B is a plan view showing a pattern which is imaged on the wafer 11. In FIG.33A, the phase shift layer 3a is formed at the edge portion of the opaque layer 14 and at the exposed portion of the transparent substrate 2 where the fine patterns are adjacent to each other. In other words, in FIG.33A there are provided an isolated region 15 and a pattern adjacent region 16.

FIG.34A shows a pattern which is formed on the wafer 11 using the mask 1A, and a description will now be given of the interference caused by the mask 1A. In FIG.34A, it is assumed that a pattern width  $g$  is fixed to 0.35  $\mu\text{m}$  and a pattern width  $h$  is varied to take the values 0.35, 0.4, 0.5, 0.6, 0.7, 0.8 and 1.0  $\mu\text{m}$ . In this case, according to the rule described above, the mask pattern for the case where the patterns with the pattern width  $h$  of 0.35, 0.4 and 0.5  $\mu\text{m}$  are adjacent becomes as shown in FIG.34B wherein the mask pattern is made up solely of the phase shift layer 3a and the white patterns are isolated. In addition, the mask pattern for the case where the patterns with the pattern width  $h$  of 0.6, 0.7, 0.8 and 1.0  $\mu\text{m}$  are isolated from each other to a certain extent becomes as shown in FIG.34C wherein a region of the opaque layer 14 exists between the white patterns.

For the sake of convenience, it is assumed that the pattern width  $h$  on the wafer 11 is 0.35  $\mu\text{m}$ . FIG.35A shows the light intensity distribution for the mask shown in FIG.34B when the mask dimension  $a$  is 0.55  $\mu\text{m}$  (reticle size of 2.75  $\mu\text{m}$ ),  $b$  is 0.15  $\mu\text{m}$  (reticle size of 0.75  $\mu\text{m}$ ) and  $c$  is 0.15  $\mu\text{m}$  (reticle size of 0.75  $\mu\text{m}$ ).

On the other hand, FIG.35B shows the light intensity distribution for the conventional mask shown in FIG.21B when the mask dimension  $e$  is  $0.35\text{ }\mu\text{m}$  (reticle size of  $1.75\text{ }\mu\text{m}$ ) and  $f$  is  $0.35\text{ }\mu\text{m}$  (reticle size of  $1.75\text{ }\mu\text{m}$ ). When FIGS.35A and 35B are compared, it can be seen that the light intensity is approximately 85 % according to this embodiment while the light intensity is approximately 55 % in the conventional case, and the contrast is improved according to this embodiment.

FIG.36 shows the light intensity distribution when the pattern width  $h$  is  $0.4\text{ }\mu\text{m}$ , FIG.37 shows the light intensity distribution when the pattern width  $h$  is  $0.5\text{ }\mu\text{m}$ , FIG.38 shows the light intensity distribution when the pattern width  $h$  is  $0.6\text{ }\mu\text{m}$ , FIG.39 shows the light intensity distribution when the pattern width  $h$  is  $0.7\text{ }\mu\text{m}$ , FIG.40 shows the light intensity distribution when the pattern width  $h$  is  $0.8\text{ }\mu\text{m}$ , and FIG.41 shows the light intensity distribution when the pattern width  $h$  is  $1.0\text{ }\mu\text{m}$ . As is also clear from FIGS.36 through 41, the light intensity is large and the contrast is improved according to this embodiment.

The following Table shows the pattern dimension of the isolated pattern 15 shown in FIG.33A for various values of the pattern width  $h$ .

Table

$h\text{ (}\mu\text{m)}$	Pattern Dimension ( $\mu\text{m}$ )
0.35	0.35
0.40	0.36
0.50	0.35
0.60	0.35
0.70	0.35
0.80	0.35
1.00	0.35
Isolated Pattern	0.35

As may be seen from the Table, the change in the pattern dimension of the isolated pattern 15 caused by the interference is within  $\pm 0.01\text{ }\mu\text{m}$ . Accordingly, it is possible to control the pattern dimension. But in order to more accurately control the pattern dimension, it is preferable to change the values of the pattern widths  $a$ ,  $b$ ,  $c$  and  $i$  in FIGS.34B and 34C.

Next, a description will be given of the case where this embodiment is applied to the formation of a contact hole pattern. FIG.42A shows the mask 1A for forming a contact hole of  $0.35\text{ }\mu\text{m}$ . According to the rule described above, the width  $a$  of the exposed portion of the transparent substrate 2 is  $0.55\text{ }\mu\text{m}$  and the width  $b$  of the phase shift layer 3a is  $0.15\text{ }\mu\text{m}$ . FIG.43A shows the light intensity distribution for this case using the mask 1A shown in FIG.42A. On the other hand, FIG.42B shows the conventional mask for forming the contact hole of  $0.35\text{ }\mu\text{m}$  without the phase shift. In this case, the width  $1$  of the exposed portion of the transparent substrate 2 is  $0.35\text{ }\mu\text{m}$ . FIG.43B shows the light intensity distribution for this case using the mask shown in FIG.42A. As may be seen from FIGS.43A and 43B, the contrast of the contact hole can be greatly improved according to this embodiment.

Next, a description will be given of third and fourth embodiments of the mask producing method according to the present invention, by referring to FIGS.44A through 44F and FIGS.45A through 45E. In FIGS.44A through 44F and FIGS.45A through 45E, those parts which are essentially the same as those corresponding parts in FIGS.14 and 15 are designated by the same reference numerals, and a description thereof will be omitted.

The transparent substrate 2 shown in FIG.44A is made of quartz, for example. The opaque layer 14 is formed on the transparent substrate 2 as shown in FIG.44B. For example, the opaque layer 14 is made of Cr and is formed to a thickness of 50 to 80 nm. A resist material 3 such as an EB resist is formed on the opaque layer 14. The resist material is subjected to a usual mask production process (not shown) including the electron beam drawing, developing, etching and resist removal steps. Thereafter, a pattern 20 of the opaque layer 14 is formed as shown in FIG.44C. The resist material 3 which is an EB resist is formed on the pattern 20, and the resist pattern 4 shown in FIG.44D is formed by electron beam drawing and developing steps. Furthermore, the phase shift layer 3s is formed on the resist pattern 4 as shown in FIG.44E. For example, the phase shift layer 3a is made of a silicon oxide and has a thickness of  $0.388\text{ }\mu\text{m}$ . Next, the resist material 3 is removed by use of a removal agent and the mask pattern layer 5 of the opaque layer 14 and the phase shift layer 3a is formed as shown in FIG.44F.

In the embodiment shown in FIG.45, the pattern 20 of the opaque layer 14 is formed similarly to the steps shown in FIGS.44A through 44C. For example, the opaque layer 14 is made of Cr and has a

thickness of 50 to 80 nm. A stopper layer 21 is formed on the pattern 20 as shown in FIG.45B. The stopper layer 21 acts as a stopper when making a plasma etching of an oxide layer on the pattern 20.

For example, the stopper layer 21 is formed on the pattern 20 by sputtering a thin film of aluminum oxide which acts as a stopper for the plasma etching which uses  $CF_4$ . The phase shift layer 3a is formed on the stopper layer 21 as shown in FIG.45C to a desired thickness. For example, the phase shift layer 3a is made of silicon oxide. The desired thickness of the phase shift layer 3a is set to  $0.388\ \mu m$  in this embodiment by use of the formula (3) so as to make a phase shift of  $180^\circ$ . The resist material 3 is formed on the phase shift layer 3a, and the resist pattern 4 is formed as shown in FIG.45D by electron beam drawing and developing steps. Then, the exposed phase shift layer 3a is etched by the  $CF_4$  plasma and the resist material 3 is removed so as to form the mask pattern layer 5 which comprises the phase shift layer 3a as shown in FIG.45E.

Next, a description will be given of a fifth embodiment of the mask producing method according to the present invention, by referring to FIGS.46A through 46E. This embodiment of the mask producing method produces a third embodiment of the mask according to the present invention shown in FIG.46E is produced. The third embodiment of the mask has a designed pattern having a width of  $1\ \mu m$ , for example, and has a structure for shifting the phase of the light wherein a region corresponding to the phase shift pattern of the glass substrate is located at a position deeper than that of the designed pattern.

In FIG.46A, a glass substrate 31 is made of quartz and has a thickness of 2 to 3 mm. An opaque layer 32 is formed on the glass substrate 31. For example, the opaque layer 32 is made of Cr and is formed on the glass substrate 31 by a sputtering CR to a thickness of 500 to 1000 Å. In addition, an aperture pattern 33 is formed in the opaque layer 32 by a normal lithography using the electron beam exposure. The aperture pattern 33 has a width of  $0.85\ \mu m$  in the case of the designed pattern having the width of  $0.35\ \mu m$ .

Next, in FIG.46B, a conductor layer 34 is formed on the glass substrate 31 for preventing charge up at the time of the electron beam exposure. For example, the conductor layer 34 is made of  $MoSi_2$  and is sputtered on the glass substrate 31 to a thickness of 200 to 300 Å. Thereafter, a negative EB resist layer 35 is formed on the glass substrate 31 and prebaked. In addition, the pattern having the width of  $0.55\ \mu m$  is subjected to an electron beam exposure approximately above the central portion of the aperture pattern 33 in the opaque layer 32. An exposed portion of the EB resist layer 35 is denoted by 35A.

Then, as shown in FIG.46C, a normal developing is made to selectively leave the exposed resist layer 35A on the designed pattern forming region. In addition, an etching process is carried out using a gas mixture of  $CCl_4$  and  $O_2$  so as to selectively remove the exposed conductor layer 34 by using the exposed resist layer 35A as a mask.

In FIG.46D, the exposed resist layer 35A and the opaque layer 32 are used as masks and an RIE which uses a gas mixture of  $CF_4$  and  $O_2$  is carried out on the top surface of the glass substrate 31 which is exposed in correspondence with phase shift patterns. Phase shift patterns 37A and 37B are formed on respective sides of a pattern 36 having a width of  $0.55\ \mu m$  on the glass substrate 31. The surface of the pattern 36 coincides with the top surface of the glass substrate 31. The phase shift patterns 37A and 37B have a width of  $0.15\ \mu m$  and has a top surface which is lower than the surface of the pattern 36. In order to shift the phase of the light which is transmitted through the phase shift patterns 37A and 37B by  $180^\circ$  with respect to the light which is transmitted through the pattern 36, the phase shift patterns 37A and 37B are etched to a depth D. When the i-ray having the wavelength of 365 nm is used for the exposure and the refractive index of glass making up the glass substrate 31 is 1.54, the depth D in this case is approximately  $0.36\ \mu m$  from the formula (1).

Next, in FIG.46E, the exposed resist layer 35A is removed by a normal ashing process. In addition, the conductor layer 34 is removed by a dry etching processing using a gas mixture of  $CCl_4$  and  $O_2$ . As a result, a mask 1C is completed. This mask 1C is the third embodiment of the mask according to the present invention.

FIG.47 shows a phase profile of the light transmitted through the mask 1C in correspondence with the mask 1C shown in FIG.46E. In FIG.47,  $i_a$  denotes the light transmitted through the central portion and  $i_b$  denotes the light transmitted through the phase shift patterns 37A and 37B.

According to the mask 1C, the phase shift pattern is made deep by using the negative resist at the time of patterning the phase shift pattern. However, when a positive resist is used the central portion is made deeper than the phase shift pattern. A fourth embodiment of the mask according to the present invention has such a structure and may be produced by steps similar to those shown in FIGS.46A through 46E.

Next, a description will be given of a sixth embodiment of the mask producing method according to the present invention, by referring to FIGS.48A through 48C. In this embodiment, a mask 1D shown in FIG.48C is produced. In FIGS.48A through 48C, those parts which are essentially the same as those corresponding parts in FIGS.46A through 46E are designated by the same reference numerals, and a description thereof



will be omitted.

In FIG.48A, the opaque layer 32 is formed on the glass substrate 31, and the aperture pattern 33 is formed in the opaque layer 32. The aperture pattern 33 has a width of 0.85  $\mu\text{m}$ . The conductor layer 34 for preventing charge up is formed on the glass substrate 31, and a positive EB resist layer 38 is thereafter  
 5 formed on the glass substrate 31. Then, an electron beam exposure is made with respect to the designed pattern which is located on the resist layer 38 at the central portion of the aperture pattern 33 in the opaque layer 32. An exposed region is denoted by 38A.

In FIG.48B, the exposed region 38A of the resist layer 38 is removed by a developing process. A dry etching using a gas mixture of  $\text{CCl}_4$  and  $\text{O}_2$  removes the conductor layer 34 exposed at an aperture 39 in  
 10 the resist layer 38. An RIE using a gas mixture of  $\text{CF}_4$  and  $\text{O}_2$  etches the top surface of the glass substrate 31 which is exposed within the aperture 39 similarly to the above described embodiment. The glass substrate 31 is etched to the depth D which is approximately 0.36  $\mu\text{m}$ .

In FIG.48C, the resist layer 38 is removed by an ashing process, and the conductor layer 34 is removed by a dry etching using a gas mixture of  $\text{CCl}_4$  and  $\text{O}_2$ . Accordingly, the mask 1D is completed.

15 FIG.49 shows a phase profile of the light transmitted through the mask 1D in correspondence with the mask 1D shown in FIG.48C. In FIG.49,  $i_c$  denotes the light transmitted through the central portion and  $i_d$  denotes the light transmitted through the phase shift patterns 41A and 41B.

Next, a description will be given of a seventh embodiment of the mask producing method according to the present invention, by referring to FIGS.50A through 50H. In FIG.50A, a transparent substrate 51 is made  
 20 of glass, quartz or the like. A phase shift layer 52 is formed on the transparent substrate 51 as shown in FIG.50B. For example, the phase shift layer 52 is made of silicon oxide and is formed by a chemical vapor deposition (CVD), a sputtering, a spin-on-glass (SOG) technique and the like. In this embodiment, the phase shift layer 52 has a thickness of 3900 Å so as to invert the phase of the light.

In FIG.50C, an opaque layer 53 is formed on the phase shift layer 52. For example, the opaque layer 53  
 25 is made of Cr and has a thickness of 700 to 1000 Å.

Next, an EB resist is formed on the opaque layer 53. Electron beam drawing, developing and etching processes are carried out with respect to the opaque layer 53. As a result, a pattern 53a of the opaque layer 53 is formed as shown in FIG.50D.

The pattern 53a of the opaque layer 53 is used as a mask when etching the phase shift layer 52 as  
 30 shown in FIG.50E. In this embodiment, the phase shift layer 52 is an oxide layer and an RIE using a gas mixture of  $\text{CF}_4$  and  $\text{CHF}_3$  is used for the etching.

Then, an EB resist layer 54 is formed as shown in FIG.50F, and an unwanted portion 53b of the opaque layer 53 is exposed by electron beam drawing and developing processes.

Finally, the EB resist layer 54 is removed and the unwanted portion 53b of the opaque layer 53 is  
 35 removed by an etching so as to complete a mask 1E. The mask 1E corresponds to a fifth embodiment of the mask according to the present invention. FIG.50H shows a plan view of the mask 1E in correspondence with FIG.50G.

Next, a description will be given of an eighth embodiment of the mask producing method according to the present invention, by referring to FIGS.51A through 51G. In FIGS.51A through 51G, those parts which  
 40 are essentially the same as those corresponding parts in FIGS.50A through 50H are designated by the same reference numerals, and a description thereof will be omitted. Steps shown in FIGS.51A through 51C respectively correspond to the steps shown in FIGS.50A through 50C, but the phase shift layer 52 is omitted in this embodiment.

In FIG.51D, the pattern 53a of the opaque layer 53 is used as a mask when etching the transparent  
 45 substrate 51. In this embodiment, an RIE using a gas mixture of  $\text{CF}_4$  and  $\text{CHF}_3$  is used for the etching, and the transparent substrate 51 is etched to a predetermined depth. When inverting the phase of the light, the predetermined depth is set to 3900 Å.

Then, an EB resist layer 54 is formed as shown in FIG.51E, and the unwanted portion 53b of the opaque layer 53 is exposed by electron beam drawing and developing processes.

50 Finally, the EB resist layer 54 is removed and the unwanted portion 53b of the opaque layer 53 is removed by an etching so as to complete the mask 1C shown in FIG.51F. FIG.51G shows a plan view of the mask 1C in correspondence with FIG.51F.

According to the seventh and eighth embodiments of the mask producing method, the opaque layer is used as a mask when etching the phase shift layer or the transparent substrate. Hence, it is possible to  
 55 prevent a positioning error between the pattern of the opaque layer and the phase shift pattern by a self-alignment.

Next, a description will be given of a ninth embodiment of the mask producing method according to the present invention, by referring to FIGS.52A through 52F. In FIGS.52A through 52F, those parts which are

essentially the same as those corresponding parts in FIGS.51A through 51G are designated by the same reference numerals, and a description thereof will be omitted.

In FIG.52A, the opaque layer 53 is formed on the transparent substrate 51 and a pattern is formed by an electron beam drawing after forming an EB resist layer (not shown) on the opaque layer 53. This pattern is developed and the opaque layer 53 is patterned by an etching. For example, the opaque layer 53 is made of Cr and is sputtered on the transparent substrate 51. The EB resist layer is removed after the patterning.

In FIG.52B, the pattern 53a of the opaque layer 53 is used as a mask when etching the transparent substrate 51 to a predetermined depth. The exposed transparent substrate 51 is etched by a parallel plate type RIE apparatus with a high-frequency excitation of 13.56 MHz. For example, the etching is carried out with a power of approximately 0.1 W/cm<sup>2</sup> at a pressure of 0.1 to 0.05 Torr using a gas mixture of CF<sub>4</sub> or CHF<sub>3</sub> and O<sub>2</sub> as the etchant gas. The etching depth is controlled to  $\lambda/2(n-1)$  by detecting the depth using an end point detector. When  $\lambda = 0.365 \mu\text{m}$ ,  $\lambda/2(n-1) = 0.39 \mu\text{m}$ .

In FIG.52C, a positive resist layer 55 (for example, OFPR-800) is formed on the transparent substrate 51 and the pattern 53c to a thickness of approximately 1.0  $\mu\text{m}$  after the etching of the transparent substrate 51 and prebaked at a temperature of 100 °C.

In FIG.52D, a light of the resist exposure region such as a monochromatic light of 40 to 60 mJ/cm<sup>2</sup> and a wavelength of 436 nm illuminates the transparent substrate 51 in its entirety from a back surface of the transparent substrate 51 so as to expose only the resist layer 55 on the transparent substrate 51. Thereafter, the transparent substrate 51 is submerged in a solution with 2.38 % of TMAH for 40 seconds, and a developing process is carried out so that only the resist layer 55 remains on the pattern 53c. Then, rinse and dry processes are carried out.

After the resist pattern is formed, a side etching is carried out to remove a portion of the pattern 53c. The side etching quantity is controlled by the etching time so that approximately 0.4 to 0.8  $\mu\text{m}$  of the opaque pattern 53 is removed on each side as shown in FIG.52E.

Finally, the resist layer 55 remaining on the opaque layer 53 is removed by an O<sub>2</sub> ashing in FIG.52F, and a mask which is substantially the same as the mask 1D shown in FIG.48C is completed.

Next, a description will be given of a tenth embodiment of the mask producing method according to the present invention, by referring to FIGS.53A through 53F. In FIGS.53A through 53F, those parts which are essentially the same as those corresponding parts in FIGS.52A through 52F are designated by the same reference numerals, and a description thereof will be omitted.

Steps shown in FIGS.53A through 53C respectively correspond to the steps shown in FIGS.52A through 52C. However, in FIG.53B, the transparent substrate 51 is etched  $\lambda/2(n-1)$ . When  $\lambda = 0.365 \mu\text{m}$ ,  $\lambda/2(n-1) = 0.39 \mu\text{m}$ .

In FIG.53D, the light of the resist exposure region illuminates the transparent substrate 51 in its entirety from the back surface of the transparent substrate 51 so as to expose only the resist layer 55 on the transparent substrate 51. Thereafter, a developing process is carried out so that only the resist layer 55 remains on the pattern 53c. Then, in this embodiment, an overexposure is made, an overdeveloping is made, or an ashing is made for a short time after the developing and drying so as to partially expose the opaque layer 53.

Next, as shown in FIG.53E, the exposed opaque layer 53 is etched using the resist layer 55 as an etching mask.

In FIG.53F, the remaining resist layer 55 on the opaque layer 53 is removed by an O<sub>2</sub> ashing. As a result, a mask which is substantially the same as the mask 1D is completed.

Next, a description will be given of an eleventh embodiment of the mask producing method according to the present invention, by referring to FIGS.54A through 54E. In FIGS.54A through 54E, those parts which are essentially the same as those corresponding parts in FIGS.52A through 52F are designated by the same reference numerals, and a description thereof will be omitted.

A step shown in FIG.54A may be the same as the step shown in FIG.52A. But in this embodiment, the resist layer 55 is formed on the transparent substrate 51 as shown in FIG.54B without etching the transparent substrate 51.

In FIG.54C, only the resist layer 55 on the transparent substrate 51 is removed similarly to the step shown in FIG.52D. Thereafter, the resist layer 55 is used as an etching mask to etch the transparent substrate 51  $\lambda/2(n-1)$ . When  $\lambda = 0.365 \mu\text{m}$ ,  $\lambda/2(n-1) = 0.39 \mu\text{m}$ .

In FIG.54D, a portion of the pattern 53c of the opaque layer 53 is removed by a side etching. A step shown in FIG.54E may be the same as the step shown in FIG.52F.

According to the embodiments described in conjunction with FIGS.52A through 54E, there is no need to match the positions of the pattern of the opaque layer and the phase shift pattern. Thus, it is possible to

produce a mask having a pattern with a high accuracy and no positioning error. In addition, the adhesion between the phase shift layer and the substrate, the cleaning and the like may be affected depending on the material used for the phase shift layer when the phase shift layer and the substrate are independent. However, according to these embodiments, a portion of the transparent substrate itself is used as the phase shift layer or phase shift region, and the material of the phase shift layer does not become a problem. Accordingly, there is no need to take into consideration the stability and durability of the material used for the phase shift layer, and it is possible to easily form fine patterns exceeding the resolution limit of the exposure apparatus.

Next, a detailed description will be given of the pattern forming method according to the present invention. FIGS.55A through 55C are diagrams for explaining the pattern forming method using the edge portion of the phase shift layer of the mask, and corresponds to FIGS.10A through 10C. In FIGS.55A through 55C, those parts which are essentially the same as those corresponding parts in FIG.12 are designated by the same reference numerals, and a description thereof will be omitted.

The phase shift layer having a refractive index  $n$  and a thickness  $t$  is formed on the transparent substrate 2 so as to constitute the mask 1. The pattern of the mask 1 is imaged on the photoresist layer 10 on the semiconductor wafer 11 via the imaging lens system 9. The desired pattern is imaged by utilizing the edge portion of the phase shift layer 3a.

The light incident to the mask 1 is transmitted through the phase shift layer 3a. Since the refractive index  $n$  of the phase shift layer 3a is different from that of air or vacuum, the phase of the transmitted light is shifted. The phase shift quantity  $S$  is described by  $S = (n - 1)t/\lambda$  or  $2\pi(n - 1)t/\lambda$  in radians. For the sake of convenience, it is assumed hereunder that the phase shift quantity  $S$  is  $\pi$  so as to invert the phase of the transmitted light.

As shown in FIG.55B, the phase of the electrical vector  $E$  of the light transmitted through the mask 1 is inverted in correspondence with the pattern of the phase shift layer 3a. When the light having the electrical vector distribution shown in FIG.55B illuminates the photoresist layer 10 and is absorbed thereby, the light intensity distribution on the photoresist layer 10 becomes proportional to  $E^2$ . Hence, as shown in FIG.55C, a black pattern PB having a narrow width is formed at the position where the phase transition occurs. In other words, when the sign of the electrical vector  $E$  changes in FIG.55B, there is a point where the electrical vector  $E$  becomes zero. The light intensity distribution is proportional to  $E^2$ , and a minimum value of the light intensity  $P$  is zero at the point where the electrical vector  $E$  is zero. Accordingly, it is possible to obtain a clear black pattern.

Generally, when the phase shift layer 3a shifts the phase of the transmitted light, it is possible to obtain a pattern in which the phase shift is spatially distributed. When the phase shift is  $180^\circ$ , the light intensity  $P$  at the position where the  $180^\circ$  phase shift occurs is always zero, and a time integral thereof is also zero. Hence, the light intensity  $P$  at the edge portion of the phase shift layer 3a is zero. When the phase shift is other than  $180^\circ$ , the sign of the electrical vector  $E$  becomes the same or the opposite depending on the time, and the time integral of the light intensity  $P$  does not become zero.

A description will now be given of an imaging using the edge portion of the phase shift layer, by referring to FIGS.56A and 56B.

FIG.56A shows the light intensity distribution for a case where the phase shift layer makes a  $180^\circ$  phase shift, that is, inverts the phase of the transmitted light. In FIG.56A, a region on the left of the abscissa 0.0 corresponds to a region in which the phase shift quantity is  $180^\circ$ , and this region is adjacent to an aperture portion on the right with the phase shift quantity of zero at the position 0.0. FIG.56A shows the light intensity distribution at one edge portion of the phase shift layer. The light intensity decreases to approximately zero at the central portion of the pattern corresponding to the end of the phase shift layer. By utilizing this imaging principle, it is possible to obtain a line pattern exceeding the conventional resolution limit.

FIG.56B shows the light intensity distribution for a case where the phase shift layer makes a  $90^\circ$  phase shift. When the phase shift quantity is  $90^\circ$ , the phase of the light transmitted through the phase shift layer and the phase of the light transmitted through the aperture portion may coincide or be inverted. Hence, the minimum value of the light intensity does not become zero when the time integral thereof is taken. In FIG.56B, the minimum value of the light intensity is approximately 0.5 or greater and is in the order of 1/2 the light intensity which is approximately 1.0 at the uniform portion. When the developing level is taken less than this light intensity, it is possible to carry out the developing in which the pattern shown is neglected. In addition, when the developing level is taken at an intermediate level between the minimum value and the uniform value of the light intensity, the pattern is developed at the central portion thereof.

Next, a description will be given of a fourth embodiment of the pattern forming method according to the present invention, by referring to FIGS.57A and 57B. FIGS.57A and 57B are diagrams for explaining the

formation of a loop shaped pattern according to this embodiment.

FIG.57A shows a mask pattern. A mask 61 is formed on an aperture 60 in the transparent substrate. The mask 61 has a phase shift quantity corresponding to an optical path difference of the half-waves of the incoming light, and shifts the phase of the transmitted light by  $180^\circ$ . When such a mask pattern is imaged, the imaged pattern becomes as shown in FIG.57B. The portion where only the aperture 60 or the phase shift layer 61 is imaged has a constant light intensity and is white. A black pattern 62 is formed at a boundary portion of the aperture 60 and the phase shift layer 61. In other words, when the light transmitted through the aperture 60 and the light transmitted through the phase shift layer 61 mix due to interference, mutually opposite phases cancel each other and the light intensity becomes zero, thereby forming a black pattern.

When the phase shift layer 61 is made of a silicon oxide and the i-ray from the mercury lamp is the light which is used for the exposure, the refractive index of the phase shift layer 61 is approximately 1.47 which has a difference of approximately 0.47 with respect to the refractive index of air which is approximately 1.00. The thickness of the phase shift layer 61 is approximately  $0.388 \mu\text{m}$ . In order to cancel the amplitude of the mixed light due to the interference, the inverted phase, that is,  $180^\circ$  phase shift, is most effective. However, the phase shift quantity is not limited to  $180^\circ$  and the light intensity can be effectively reduced within the range of  $180^\circ \pm 30\%$ .

When the phase shift layer 61 having the phase shift quantity of  $180^\circ$  is formed above the aperture which makes no phase shift as in the case of the mask pattern shown in FIG.57A, a black pattern is formed at the portion corresponding to the edge portion of the phase shift layer 61. In this case, the black pattern has a closed loop shape.

FIGS.58A and 58B respectively show a mask pattern for forming an open shape (line segment) and an imaged pattern thereof.

In FIG.58A, the phase shift layer 61 is formed above the aperture 60, and one side of the phase shift layer 61 is used for forming a line segment. A phase shift layer 64 having a phase shift quantity of  $90^\circ$  is formed adjacent to the remaining (unwanted) sides of the phase shift layer 61. In other words, out of the four sides of the phase shift layer 61 having the phase shift quantity of  $180^\circ$ , one side 61a forms a boundary with a region in which the phase shift quantity is zero, and this side 61a forms a black pattern 65 in the imaged pattern as shown in FIG.58B. The other sides 61b, 61c and 61d are adjacent to the phase shift layer 64 which has the phase shift quantity of  $90^\circ$ . Hence, the phase shift when crossing these sides 61b, 61c and 61d is  $90^\circ$ , and the decrease in the light intensity is small at the edge portion of the phase shift layer 61 corresponding to these sides 61b, 61c and 61d. The peripheral sides of the phase shift layer 64 also have the phase shift quantity of  $90^\circ$  and the decrease in the light intensity is similarly small. It is possible to leave only the black pattern 65 by adjusting the developing level. In this case, a gray level is formed between the white and black levels, but it is of course possible to use two or more halftones.

By using a plurality of kinds of phase shift layers having different phase shift quantities, it is possible to form the pattern of an open shape such as a line segment.

FIGS.59A and 59B respectively show a mask pattern for forming a dot pattern and an imaged pattern thereof.

In FIG.59A, the phase shift layer 61 having the phase shift quantity of  $180^\circ$  is formed above the aperture 60. The phase shift layer 64 which has the phase shift quantity of  $90^\circ$  surrounds the phase shift layer 61 excluding one vertex portion thereof. In other words, the phase shift layer 61 is adjacent to the aperture 60 at only the one vertex portion of the phase shift layer 61. When such a mask pattern is imaged, the imaged pattern becomes as shown in FIG.59B in which a black pattern 66 is formed only at the portion where the phase shift layer 61 and the aperture 60 connect. Because the phase shift quantity is  $90^\circ$  at the boundary of the phase shift layers 61 and 64, the decrease in the light intensity at this boundary is small compared to that at the portion corresponding to the black pattern 66. In addition, the outer peripheral portion of the phase shift layer 64 also has the phase shift quantity of  $90^\circ$ , and the decrease in the light intensity is similarly small. For this reason, it is possible to develop only the black pattern 66 as the pattern and treat the other patterns in the halftones as white patterns.

A description is given heretofore with respect to the cases where the pattern to be formed is a line segment pattern. But in the following, a description will be given of the formation of a pattern which has an intersection.

FIGS.60A and 60B show mask patterns for forming an intersecting pattern, and FIG.60C shows an imaged pattern which is formed by the mask patterns shown in FIGS.60A and 60B.

FIG.60A shows a first mask pattern. The surface of the mask pattern is divided into four quadrants in correspondence with the regions which are divided by the intersecting lines. The aperture 60 which makes no phase shift is provided in the first quadrant. The phase shift layer 61 which has the phase shift quantity

of  $180^\circ$  is provided in the two quadrants which are adjacent to the aperture 60. A phase shift layer 67 which has a phase shift quantity of  $360^\circ$  is provided in the remaining quadrant. In other words, the boundary between two quadrants has a phase shift quantity of  $180^\circ$ .

FIG.60B shows a second mask pattern. Similarly to the first mask pattern shown in FIG.60A, the surface of the mask pattern shown in FIG.60B is divided into four quadrants. The aperture 60 which makes no phase shift is provided in the first quadrant. The phase shift layer 61 which has the phase shift quantity of  $180^\circ$  is provided in the two quadrants adjacent to the aperture 60. An aperture 68 which makes no phase shift is provided in the remaining quadrant. In this case, the boundary between two quadrants also has a phase shift quantity of  $180^\circ$ .

When the mask patterns shown in FIGS.60A and 60B are imaged, an imaged pattern shown in FIG.60C is obtained. That is, a portion having a uniform phase is imaged as a white pattern, and a portion having the  $180^\circ$  phase shift is imaged as a black pattern 69.

The intersecting lines are not limited to straight lines and may be curved.

FIGS.61A and 61B respectively show a mask pattern for forming a T-shaped pattern and an imaged pattern thereof.

In FIG.61A, phase shift layers 61a and 61b having the phase shift quantity of  $180^\circ$  are formed adjacent to the aperture 60 which makes no phase shift. In addition, the aperture 68 which makes no phase shift is formed above the phase shift layer 61a so as to form a boundary having the phase shift quantity of  $180^\circ$ . As a result, a black pattern shown in FIG.61B is imaged when this mask pattern is imaged. Furthermore, since a black pattern will be imaged if the phase shift layers 61b and 68 are directly adjacent to each other and form a boundary having the phase shift quantity of  $180^\circ$ , a phase shift layer 71 which has a phase shift quantity of  $90^\circ$  is formed between the phase shift layers 61b and 68. In other words, the decrease in the light intensity is relatively small at the boundary of the phase shift layer 71 because the phase shift quantity is only  $90^\circ$ . By appropriately adjusting the developing threshold value, such a decrease in the light intensity can be developed as a white pattern. As a result, a black pattern 72 shown in FIG.61B is imaged.

In FIG.61A, there is a gap between the aperture 68 and the phase shift layer 61b. However, such a gap may be reduced if needed.

In semiconductor devices, there is often a need to provide a wide region for making a contact at an intermediate part of an interconnection pattern. FIGS.62A through 62C show mask patterns for forming such an interconnection pattern, and FIG.62D shows an imaged pattern thereof.

In FIG.62A, the aperture 60 which makes no phase shift and the phase shift layer 61 which has the phase shift quantity of  $180^\circ$  are adjacent to each other and forms a linear boundary. A phase shift layer having a phase shift quantity of  $180^\circ$  is formed within the aperture 60 at the central portion of the boundary. An aperture 70 which makes no phase shift is formed in the phase shift layer 61. The aperture 74 and the phase shift layer 75 both have a rectangular shape, and a boundary therebetween is aligned to the linear boundary between the aperture 60 and the phase shift layer 61. In FIG.62A, all the boundaries indicated by the solid line accompanies a  $180^\circ$  phase shift.

In FIG.62B, the boundary which defines each region is formed similarly to FIG.62A. However, the aperture 74 shown in FIG.62A is replaced by a phase shift layer 76 which has a phase shift quantity of  $360^\circ$ . As in the case of the mask pattern shown in FIG.62A, there is a  $180^\circ$  phase shift between the upper and lower regions bounded by the straight horizontal boundary. In addition, a rectangular boundary having the phase shift quantity of  $180^\circ$  is formed at the central portion of the mask pattern.

In FIG.62C, the mask pattern is generally divided into two regions by a straight horizontal boundary. In the upper region, the aperture 60 which makes no phase shift is formed on the right and the phase shift layer 61 which has the phase shift quantity of  $180^\circ$  is formed on the left. The aperture 60 and the phase shift layer 61 are adjacent to each other for a limited length. In addition, a phase shift layer 77 which has an intermediate phase shift quantity of  $90^\circ$  is formed between the aperture 60 and the phase shift layer 61. The lower region has a structure similar to that of the upper region. That is, in the lower region, the aperture 68 which makes no phase shift is formed on the left below the phase shift layer 61, and the phase shift layer 61 which has the phase shift quantity of  $180^\circ$  is formed on the right below the aperture 60. The aperture 68 and the phase shift layer 61 in the lower region are adjacent to each other for a limited length. In addition, the phase shift layer 77 which has the intermediate phase shift quantity of  $90^\circ$  is formed between the aperture 68 and the phase shift layer 61 in the lower region. As a whole, a boundary which accompanies a  $180^\circ$  phase shift is formed along the straight horizontal line and also at a vertical line segment portion at the central portion of the mask pattern.

FIG.62D shows an imaged pattern which is obtained when the mask patterns shown in FIGS.62A through 62C are imaged. In this case, a black pattern 78 which has a wide region at the central portion is imaged.

When making the length of the line finite in the mask patterns shown in FIGS.60A, 60B, 61A, 62A, 62B and 62C, it is sufficient to form in an unwanted portion a region having an intermediate phase shift quantity of  $90^\circ$  or the like.

The mask patterns for forming various imaged patterns are described above, and now, a description will be given of the light intensity profiles which are obtained by numerical calculations for some of the described mask patterns.

For the calculations, it is assumed for the sake of convenience that the light used for the exposure has a wavelength of 365 nm, the imaging lens system has a numerical aperture NA of 0.50, and the light from the illumination lens system has a partial coherency  $\sigma$  of 0.50.

FIGS.63A through 63C are diagrams for explaining the pattern of intersecting lines.

FIG.63A generally shows a pattern and a sampling region of the intersecting lines. The mask pattern shown in FIG.60B is employed, and the X, Y and Z coordinates shown on the right in FIG.63A is used. In addition, a region indicated by a phantom line is regarded as the sampling region, and the light intensity within the sampling region is calculated according to a mode. FIG.63B is a graph showing the light intensity profile within the sampling region shown in FIG.63A as a three dimensional model. It may be seen from FIG.63B that a deep valley is formed at the boundary portion accompanying the  $90^\circ$  phase shift. Although FIG.63B does not show the light intensity profile for the lower half portion of the pattern shown in FIG.63A, it is apparent to those skilled in the art that the light intensity profile has a structure similar to that shown in FIG.63B for the lower half portion of the pattern shown in FIG.63A. FIG.63C shows a projection of the light intensity profile shown in FIG.63B on an XY plane when the light intensity profile is described by contour lines with respect to the light intensity. In other words, regions with the minimum light intensity are formed at a portion extending along the lower side in the direction X and a portion extending along the central portion in the direction Y. Portions where the light intensity gradually increases are formed adjacent to such regions with the minimum light intensity.

FIGS.64A through 64C are diagrams for explaining the pattern of interconnections.

FIG.64A shows the mask pattern for the interconnection pattern shown in FIG.62A, and a sampling region is indicated by a phantom line. The X, Y and Z coordinates shown on the right of FIG.64A is used.

FIG.64B shows a light intensity profile within the sampling region shown in FIG.64A. A narrow valley is formed along the direction X, and the valley portion widens in a vicinity of a region in which  $X = 0$ . FIG.64C shows a projection of the light intensity profile shown in FIG.64B on the XY plane when the light intensity profile is described by contour lines with respect to the light intensity. It may be seen from FIG.64C that a valley portion is formed and the width of this valley portion widens at the central portion.

FIGS.65A through 65C are diagrams for explaining the pattern of interconnections.

FIG.65A shows the mask pattern for the interconnection pattern shown in FIG.62C, and a sampling region is indicated by a phantom line. On the horizontal axis at the central portion of FIG.65A there are formed the aperture 60 which makes no phase shift and the phase shift layer 61 which has the phase shift quantity of  $180^\circ$ . The aperture 60 and the phase shift layer 61 are adjacent to each other in part and the phase shift layer 77 which has the phase shift quantity of  $90^\circ$  is formed between the aperture 60 and the phase shift layer 61. In addition, the upper side of the aperture 60 makes an angle  $\theta_1$  to the horizontal direction. The two sides of the phase shift layer (intermediate region) 77 make an angle  $\theta_2$ . Further, the upper side of the phase shift layer 61 makes an angle  $\theta_3$  to the horizontal direction. The phase shift layer 61 which has the phase shift quantity of  $180^\circ$  is formed adjacent to and symmetrically to the aperture 60 below the horizontal axis, and the aperture 68 which makes no phase shift is formed below the phase shift layer 61. In addition, another phase shift layer 77 is formed below the horizontal axis at a position symmetrical to the phase shift layer 77 above the horizontal axis. A narrow region at the central portion where the apertures 60 and 68 and the phase shift layer 61 meet has a width  $W_1$ . In this sample,  $\theta_1 = \theta_2 = \theta_3 = 60^\circ$ , and  $W_1 = 0.2 \mu\text{m}$ . FIGS.65B and 65C show the imaged pattern which is formed using such a mask pattern.

FIG.65B shows a light intensity profile within the sampling region shown in FIG.65A. A deep valley is formed along the direction X, and the valley extends in the direction Y at the central portion. Moreover, a shallow branching valley is formed as shown.

FIG.65C shows a projection of the light intensity profile shown in FIG.65B on the XY plane when the light intensity profile is described by contour lines with respect to the light intensity.

FIGS.66A through 66C are diagrams for explaining a mask pattern having a structure similar to the mask pattern shown in FIG.59A.

In FIG.66A, the aperture 60 which makes no phase shift is formed on the right and the phase shift layer 61 which has the phase shift quantity of  $180^\circ$  and a triangular shape is formed on the left. The aperture 60 and the phase shift layer 61 are adjacent to each other for a width  $W_2$ . In addition, the phase shift layer 64

which has the phase shift quantity of  $90^\circ$  is formed in each intermediate region between the aperture 60 and the phase shift layer 61. The light intensity distribution is calculated for a sampling region indicated by a phantom line. For example, a gap of  $0.08 \mu\text{m}$  is set for the width  $W_2$ , and two boundary lines which are formed by the phase shift layer 61 and the two phase shift layers 64 make an angle of  $60^\circ$ .

FIG.66B shows the light intensity distribution within the sampling region shown in FIG.66A, and FIG.66C shows a projection of the light intensity profile shown in FIG.66B on the XY plane when the light intensity profile is described by contour lines with respect to the light intensity. As may be seen from FIG.66C, an oval region in which the light intensity is a minimum is formed in a vicinity of the position (0.0).

FIGS.67A and 67B are diagrams for explaining a line-and-space pattern.

FIG.67A shows a mask pattern for the line-and-space pattern. The line-and-space pattern is formed by an aperture region 80 and a phase shift region 81 which are alternately formed, where the aperture region 80 makes no phase shift and the phase shift region 81 has a phase shift quantity of  $180^\circ$ . For example, when the widths of the aperture region 80 and the phase shift region 81 respectively are  $0.5 \mu\text{m}$  and the light intensity profile of the imaged pattern is calculated, the light intensity profile shown in FIG.67B is obtained. A minimum of the light intensity is formed at a portion corresponding to the boundary between the aperture region 80 and the phase shift region 81. When making the calculation, it is assumed for the sake of convenience that the light used for the exposure has the wavelength of  $365 \text{ nm}$ , the numerical aperture NA of the lens system is  $0.53$ , and the partial coherency  $\sigma$  of the light is  $0.5$ .

FIGS.68A and 68B are diagrams for forming a pattern in which various pattern sizes are mixed.

FIG.68A shows a mask pattern. An opaque layer 85 for forming a large black pattern and a phase shift layer 86 are combined at the upper part. A phase shift layer 87 for forming the image of the phase shift layer itself is formed at the intermediate part. A phase shift layer 88 for forming an imaged pattern by the edge portion thereof is formed at the lower part. A phase shift layer 89 which has an intermediate phase shift quantity for preventing the imaging of the unwanted sides is formed in the periphery of the phase shift layer 88. For example, the phase shift layers 86, 87 and 88 have a phase shift quantity of  $180^\circ$ , and the phase shift layer 89 has a phase shift quantity of  $90^\circ$ . When the lens system used has a numerical aperture NA of  $0.4$  to  $0.6$  for the i-ray, the pattern of  $0.5 \mu\text{m}$  or greater is formed by arranging the phase shift region 86 with the phase shift quantity of  $90^\circ$  around the opaque layer 85 as shown in the upper part of FIG.68A. When forming the black pattern of  $0.3$  to  $0.5 \mu\text{m}$ , the mask is formed solely by the pattern of the phase shift layer 87 having the phase shift quantity of  $180^\circ$ , as shown in the intermediate part of FIG.68A. The pattern of  $0.25 \mu\text{m}$  or less is formed by the boundary of the phase shift layer 88 which has the phase shift quantity of  $180^\circ$  and an aperture region 90 which makes no phase shift, as shown in the lower part of FIG.68A. In this case, the side of the unwanted phase shift region 88 is surrounded by the phase shift layer 89 which has the intermediate phase shift quantity so as not to be imaged by adjusting the developing level.

FIG.68B shows the imaged pattern which is obtained by use of the mask pattern shown in FIG.68A. A black pattern 91 which corresponds to the mask which is made up of the opaque layer 85 and the phase shift region 86 is formed at the upper part. A black pattern 92 which corresponds to the phase shift layer 87 is formed at the intermediate part. A narrow black pattern 93 which corresponds to the boundary between the phase shift layer 88 and the aperture region 90 is formed at the lower part.

When producing an integrated circuit by the photolithography, the pattern of the reticle is imaged on the wafer using an imaging lens system. Accompanied by the increase in the integration density of the integrated circuit, the numerical aperture NA of the imaging lens system is increased so as to improve the resolution and cope with the fine integrated circuit patterns. However, when the numerical aperture NA is made large so as to improve the resolution, the focal point depth FD becomes small according to the following formula (4), where  $K_2$  denotes a process coefficient.

$$FD = K_2(\lambda/NA_2) \quad (4)$$

Accordingly, it is impossible to accurately form the pattern with respect to a concavoconvex surface.

Next, a description will be given of an embodiment which can satisfactorily form a pattern even with respect to a concavoconvex surface. FIG.69 shows a sixth embodiment of the mask according to the present invention. In FIG.69, those parts which are essentially the same as those corresponding parts in FIG.9 are designated by the same reference numerals, and a description thereof will be omitted. In this embodiment, the phase shift layer 3a comprises a shifter portion 3a1 having a thickness  $D_1$  and a shifter portion 3a2 having a thickness  $D_2$ , where  $D_2 > D_1$ . By providing such shifter portions which have different thicknesses, it is possible to arbitrarily control the focal point of the image when making the exposure.

Next, a description will be given of a fifth embodiment of the pattern forming method according to the present invention. In this embodiment, the thickness of the phase shift layer of the mask is made different locally where needed. For the sake of convenience, it is assumed that the mask 1A shown in FIG.19 and the optical system shown in FIG.22 is used to form the pattern, and a description will be given of the relationship of the thickness of the phase shift layer 3a and the deviation (defocus quantity) of the focal position. The light used for the exposure, the material used for the phase shift layer 3a and the like are the same as those of the embodiment described above. When the thickness  $t$  of the phase shift layer 3a is calculated for obtaining each phase shift quantity  $S$  of  $180^\circ$ ,  $120^\circ$  and  $240^\circ$ , respectively,  $t = 0.388$ ,  $0.259$  and  $0.517 \mu\text{m}$ .

First, when  $t = 0.388 \mu\text{m}$  and  $S = 180^\circ$ , the light intensity distribution becomes as shown in FIG.71C when the defocus quantity is zero. However, when the defocus quantities are set to  $+1.0$  and  $+0.5 \mu\text{m}$  by taking as the positive (+) direction the direction towards the wafer 11 along the optical axis of the lens system 9, the light intensity distributions become as shown in FIGS.70A and 70B, respectively. On the other hand, when the defocus quantities are set to  $-0.5$  and  $-1.0 \mu\text{m}$ , the light intensity distributions become as shown in FIGS.70D and 70E, respectively. As may be seen from FIGS.70A through 70E, the light intensity distribution changes in the same manner regardless of whether the focal point deviates in the positive direction or the negative direction.

FIGS.71A, 71B, 71C and 71D respectively show the light intensity distributions which are obtained when  $t = 0.259 \mu\text{m}$ ,  $S = 120^\circ$  and the defocus quantities are to  $+1.0$ ,  $+0.5$ ,  $0$  and  $-0.5 \mu\text{m}$ . As may be seen from FIGS.71A through 71D, the contrast is a maximum when the defocus quantity is  $+0.5 \mu\text{m}$ .

FIGS.72A, 72B, 72C and 72D respectively show the light intensity distributions which are obtained when  $t = 0.517 \mu\text{m}$ ,  $S = 240^\circ$  and the defocus quantities are to  $+0.5$ ,  $0$ ,  $-0.5$  and  $-1.0 \mu\text{m}$ . As may be seen from FIGS.72A through 72D, the contrast is a maximum when the defocus quantity is  $-0.5 \mu\text{m}$ .

According to this embodiment, the focal point can be controlled within the range of  $0.5 \mu\text{m}$  by appropriately determining the thickness  $t$  of the phase shift layer.

In the production process of the integrated circuit, a region of the integrated circuit may have a height greater than that at other regions. For example, in the dynamic random access memory (DRAM), the memory cell part is  $0.5$  to  $1.0 \mu\text{m}$  higher than the other peripheral circuit parts when stacked capacitors are used. In such a case, when an attempt is made to form the pattern to the resolution limit by using a lens system having a large numerical aperture NA, the focal point depth FD becomes small and it is difficult to apply the pattern formation to the production of integrated circuits having concavoconvex surfaces.

However, according to this embodiment, it is possible to apply the pattern formation to the DRAM using stacked capacitors as shown in FIG.73. In FIG.73, those parts which are essentially the same as those corresponding parts in FIGS.22 and 69 are designated by the same reference numerals, and a description thereof will be omitted. In this case, the pattern formation of the lower portion of the integrated circuit such as the peripheral circuit part of the DRAM is made by use of the thinner shifter portion 3a1 of the phase shift layer 3a. Accordingly,  $D1$  is set smaller than  $0.388 \mu\text{m}$ . For example, when the difference in the heights of the cell part and the peripheral circuit part of the DRAM is approximately  $1.0 \mu\text{m}$ ,  $D1$  is set to  $0.259 \mu\text{m}$ . On the other hand, the pattern formation of the high portion of the integrated circuit such as the cell part of the DRAM is made by use of the thicker shifter portion 3a2 of the phase shift layer 3a. Hence,  $D2$  is set greater than  $0.388 \mu\text{m}$ . For example,  $D2$  is set to  $0.517 \mu\text{m}$  when the cell part is approximately  $1 \mu\text{m}$  higher than the peripheral circuit part of the DRAM.

By controlling the thickness of the phase shift layer depending on the concavoconvex surface of the integrated circuit, it is possible to form the pattern by matching the focal point to all surface portions of the integrated circuit.

As described heretofore in conjunction with the various embodiments, the present invention forms the pattern by utilizing the phase shift layer. For this reason, it is possible to form an arbitrary fine pattern by use of a mask in which the phase shift layer is appropriately arranged. FIGS.74A, 75A, 76A and 77A show examples of mask patterns and FIGS.74B, 75B, 76B and 77B respectively show patterns which can be formed by use of the mask patterns shown in FIGS.74A, 75A, 76A and 77A. In FIGS.74A through 77B, there are provided an opaque layer 90, a phase shift layer 91 and an aperture (window) 92.

In the described embodiments, the partial coherency  $\sigma$  is set to  $0.5$ . However, the partial coherency  $\sigma$  is not limited to  $0.5$  and may be set within the range of  $0.3 \leq \sigma \leq 0.7$ .

In addition, the light which is used for the exposure is not limited to the i-ray. Moreover, the light use for the exposure may illuminate the mask from the side of the transparent substrate provided within the phase shift layer or from the other side of the transparent substrate not provided with the phase shift layer. The materials used for the transparent substrate and the phase shift layer are of course not limited to those of the described embodiments. For example, the transparent substrate may be made of any material as long



as the transparent substrate is transparent with respect to the light which is used for the exposure. Furthermore, the phase shift layer may be made of a material selected from a group including  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{MgF}_2$ .

The masks described in the embodiments include reticles. Accordingly, the pattern forming method according to the present invention is not limited to the application to the formation of patterns of semiconductor devices, and may of course be applied to the formation of patterns of masks and reticles.

Further, the present invention is not limited to these embodiments, but various variations and modifications may be made without departing from the scope of the present invention.

## 10 Claims

1. A mask for use in exposure of a semiconductor wafer, including:  
transparent portions (2, 31, 51) for transmitting light used in the exposure, formed by a transparent layer and corresponding to first areas of said wafer, these being areas which are to be exposed;  
15 opaque portions (14, 32, 53) for masking said light, formed by an opaque layer and corresponding to second areas of said wafer adjacent to said first areas; and  
phase shift portions (3a, 37A, 37B, 41A, 41B) for shifting the phase of said light so as to improve the contrast between the first and second areas, formed by a phase shift layer (3a) formed over the transparent layer and the opaque layer;  
20 characterized in that in at least one part of the mask, said phase shift portions are formed only along edges of said opaque portions (14, 32, 53) without extending between adjacent opaque portions.
2. The mask as claimed in claim 1, wherein the phase shift portions (3a, 37A, 37B, 41A, 41B) produce a phase shift of said light within a range of  $180^\circ \pm 30\%$ .
- 25 3. The mask as claimed in claim 1 or 2, wherein a said phase shift portion (3a, 37A, 37B, 41A, 41B) is provided at an edge portion of said opaque layer (14, 32, 53) for forming a line pattern when making the exposure.
- 30 4. The mask as claimed in claim 1, 2, or 3, wherein a said phase shift portion (3a, 37A, 37B, 41A, 41B) is provided at a pair of edge portions of said opaque layer (14, 32, 53) for forming a pattern of arbitrary width when making the exposure.
- 35 5. The mask as claimed in claim 4, wherein a boundary between said phase shift portions (3a, 37A, 37B, 41A, 41B) and said transparent portions (2, 31, 51) is located on an inner side of a designated black pattern.
- 40 6. The mask as claimed in any of claims 1 to 5, wherein the phase shift portions (3a, 37A, 37B, 41A, 41B) include a first portion (3a1) and a second portion (3a2) which have mutually different thicknesses.
7. The mask as claimed in any preceding claim, wherein the transparent layer (2, 31, 51) is made of quartz or glass.
- 45 8. The mask as claimed in any preceding claim, wherein the phase shift layer (3a) is made of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , or  $\text{MgF}_2$ .
9. The mask as claimed in any preceding claim, wherein the opaque layer (14, 32, 53) is made of Cr.
- 50 10. A method of producing a mask as claimed in any preceding claim, comprising the steps of:  
forming said opaque layer (14, 20) on said transparent layer (2);  
forming a resist pattern (4) which is made of a resist material, on said opaque layer;  
forming the phase shift layer (3a) which transmits the light on said resist pattern layer to a predetermined thickness; and  
removing said resist pattern layer, whereby said phase shift layer remains on said transparent layer  
55 and said opaque layer only in a vicinity of an edge portion of said opaque layer in at least one part of the mask.

11. A method of producing a mask as claimed in any one of claims 1 to 9, comprising the steps of:  
 forming said opaque layer (14, 20) on said transparent layer (2);  
 forming a stopper layer (21) on said opaque layer;  
 forming the phase shift layer (3a) on said opaque layer to a predetermined thickness;  
 5 forming a resist pattern (4) made of a resist material, on said phase shift layer; and  
 etching said phase shift layer using said stopper layer as an etching stopper and said resist pattern  
 as an etching mask, whereby said phase shift layer remains on said stopper layer only in a vicinity of  
 an edge portion of said opaque layer in at least one part of the mask.
12. The method as claimed in claim 11, wherein the stopper layer is made of  $\text{Al}_2\text{O}_3$ .
13. A pattern forming method for forming a pattern on a semiconductor wafer (11) using a mask as claimed  
 in any of claims 1 to 9, the method comprising illuminating the mask (1, 1A-1G) by light from a light  
 source, and projecting the light transmitted through the mask onto a photoresist layer (10) formed on  
 15 the wafer by use of a lens system (9), whereby the photoresist layer is developed in said first areas of  
 the wafer corresponding to the transparent portions (2) of the mask.
14. The pattern forming method as claimed in claim 13, wherein the light is projected at different focal  
 positions on the photoresist layer (10) depending on a concavoconvex surface structure of said  
 20 photoresist layer.
15. The pattern forming method as claimed in claim 13 or 14, wherein a black pattern (PB) is projected on  
 the photoresist layer (10) which has a light intensity lower than that at other portions of the photoresist  
 layer, using interference generated in the vicinity of an edge portion of said opaque layer (14, 32, 53).
- 25 16. The pattern forming method as claimed in claim 13 or 14, wherein a white pattern is projected on the  
 photoresist layer (10) which has a light intensity higher than that at other portions of the photoresist  
 layer using interference generated in the vicinity of an edge portion of the opaque layer (14, 32, 53).
- 30 17. The pattern forming method as claimed in claim 14, 15, or 16, wherein said light is partially coherent  
 with a coherency in the range 0.3 to 0.7.
18. The pattern forming method as claimed in any of claims 13 to 17, wherein the mask has mutually  
 adjacent phase shift portions with mutually different phase shift quantities, the difference in phase shift  
 35 quantities being in the range  $90^\circ$  to  $180^\circ$ , and wherein a black pattern is generated on said resist by a  
 boundary of the adjacent phase shift portions with a  $180^\circ$  phase shift quantity difference, and no  
 pattern is generated on said resist by a boundary of the phase shift portions with a phase shift quantity  
 difference of  $90^\circ$  or less.
- 40 19. The pattern forming method as claimed in any of claims 13 to 17, wherein the mask has mutually  
 adjacent phase shift portions with mutually different phase shift quantities, the difference in phase shift  
 quantities being in the range  $90^\circ \pm 30\%$  to  $180^\circ \pm 30\%$ .

FIG. 1 (PRIOR ART)

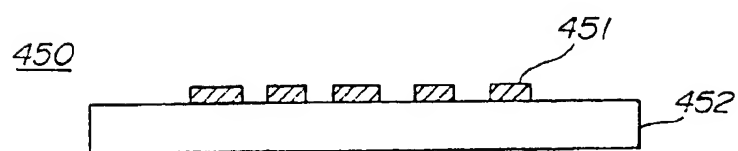


FIG. 2 (PRIOR ART)

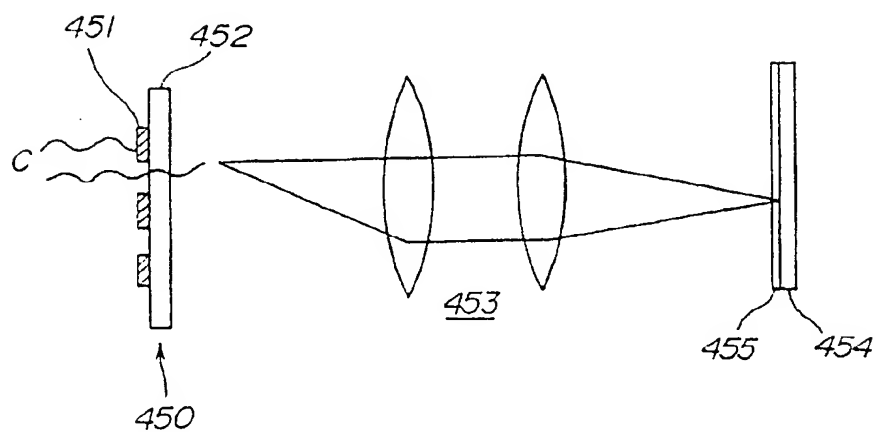


FIG. 3 A

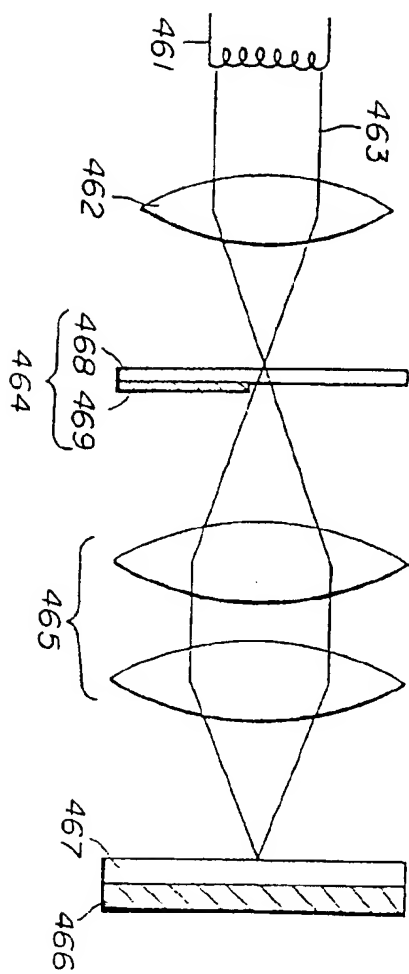


FIG.3B  
(PRIOR ART)

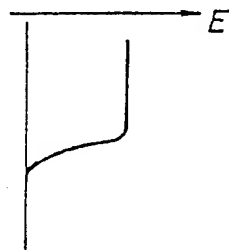


FIG.3C  
(PRIOR ART)

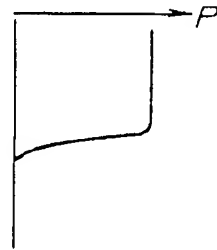


FIG.3D (PRIOR ART)

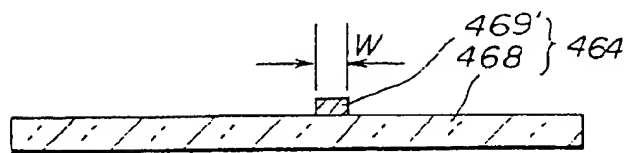


FIG. 4 A (PRIOR ART)

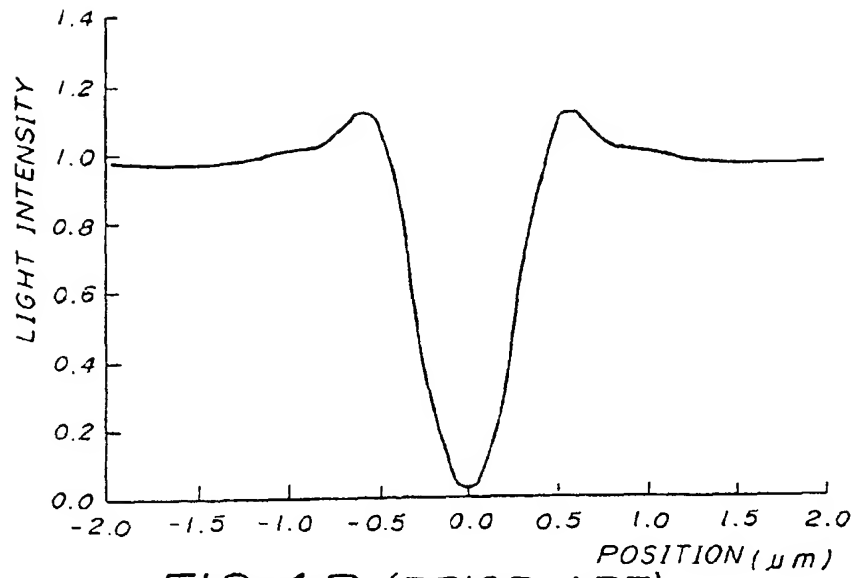


FIG. 4 B (PRIOR ART)

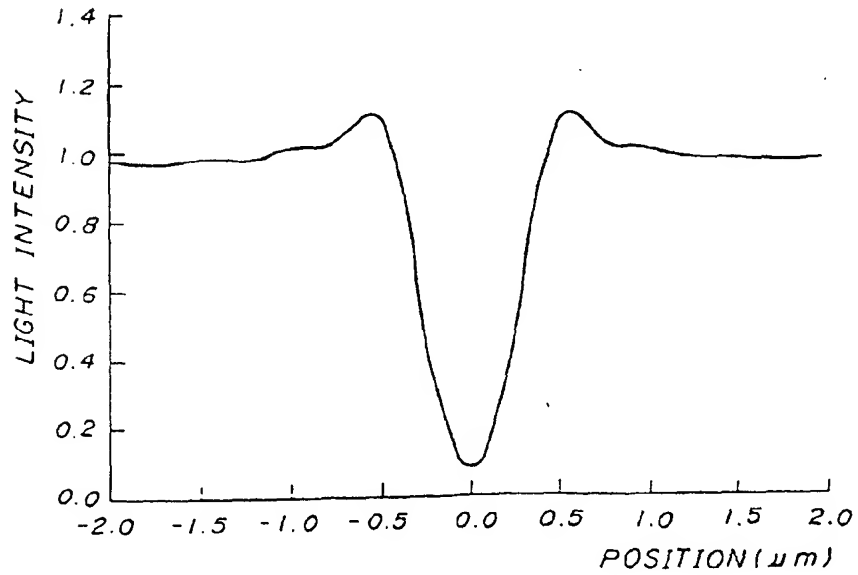


FIG.4 C (PRIOR ART)

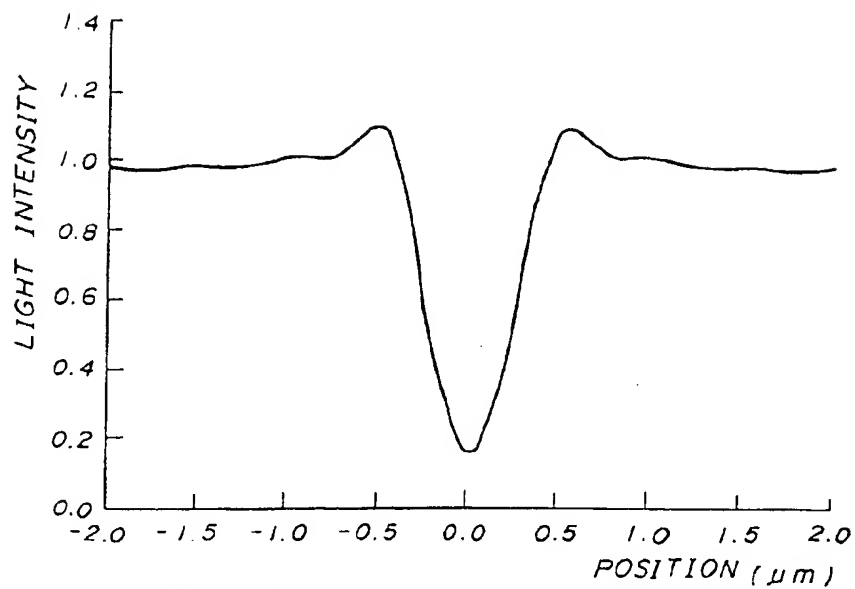
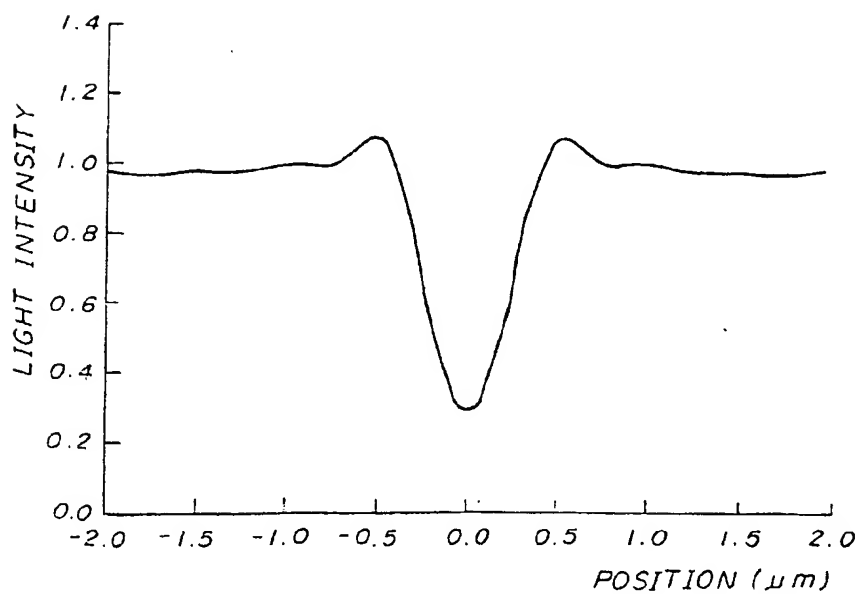


FIG.4 D (PRIOR ART)



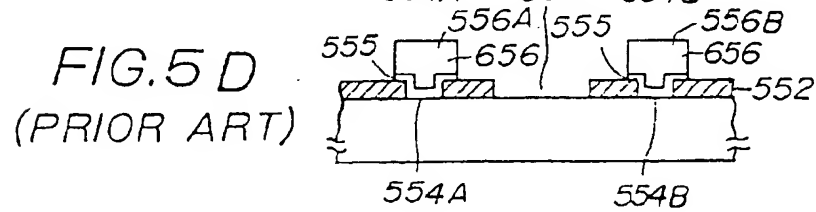
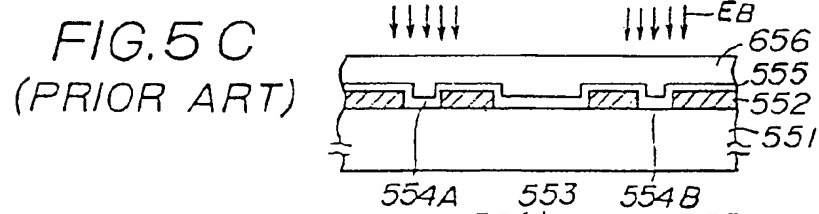
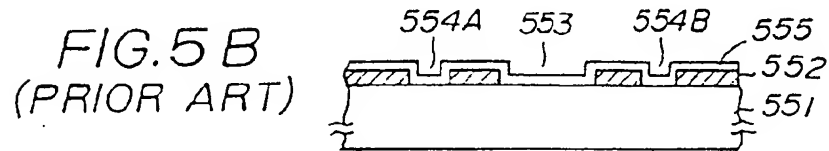
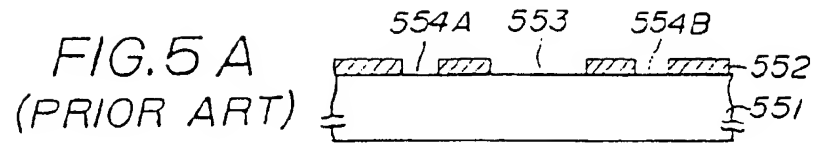


FIG. 6 (PRIOR ART)

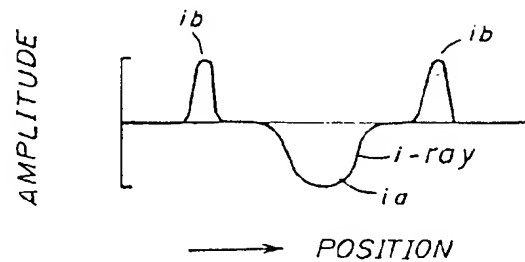




FIG.7 (PRIOR ART)

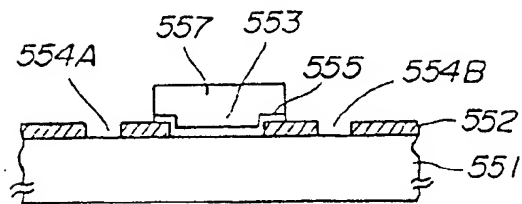


FIG.8

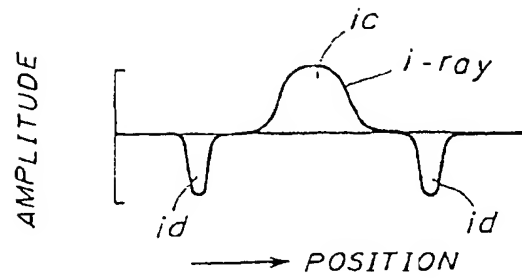


FIG. 9

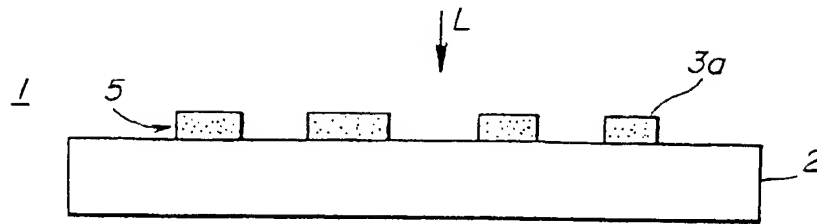


FIG. 12

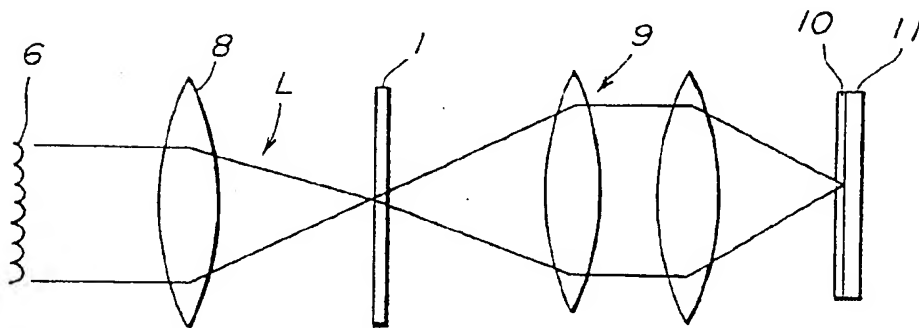
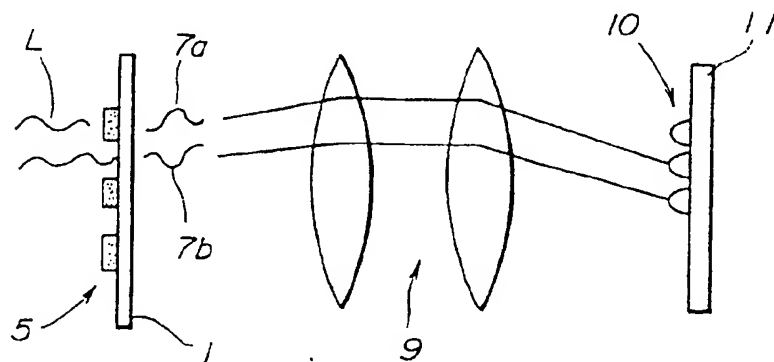


FIG. 13



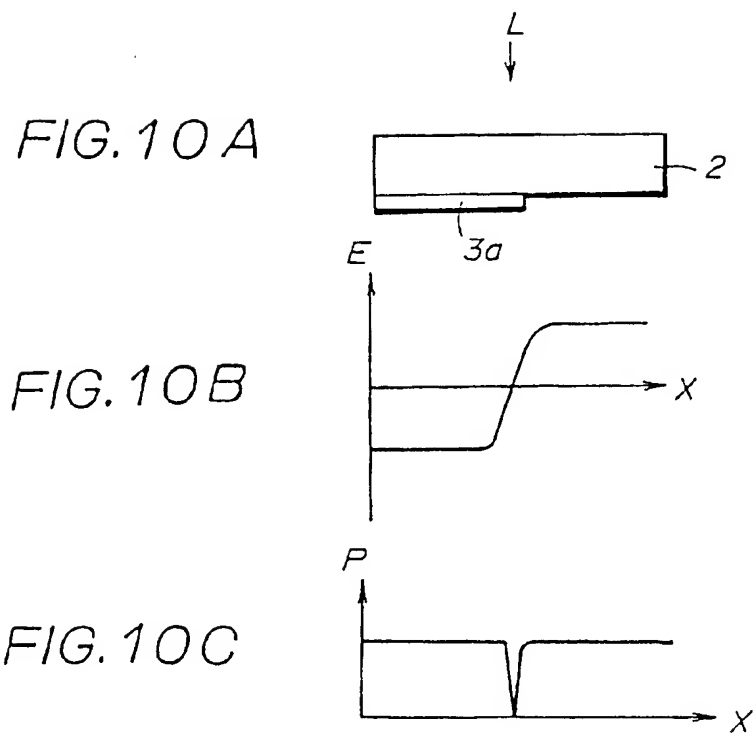


FIG. 11A

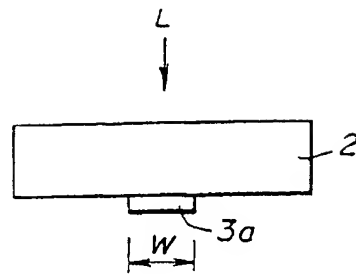


FIG. 11B

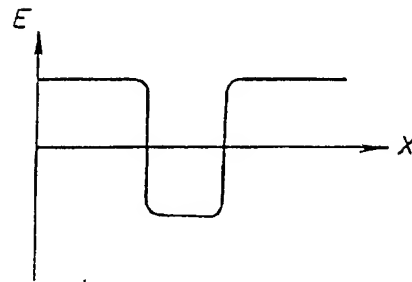


FIG. 11C

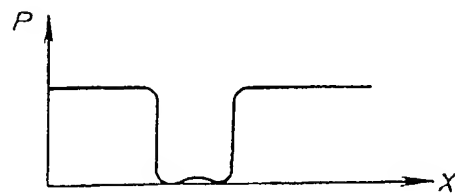


FIG. 14A

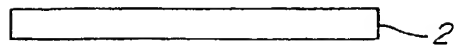


FIG. 14B

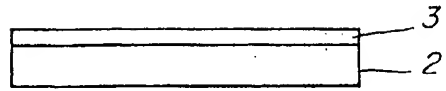


FIG. 14C

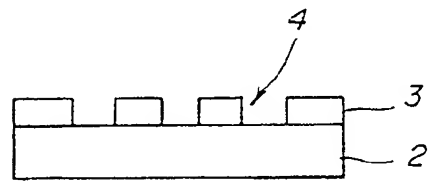


FIG. 14D

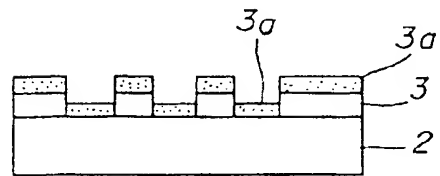
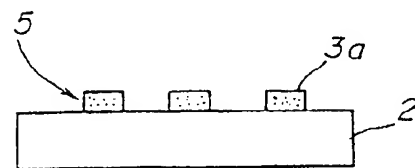


FIG. 14E



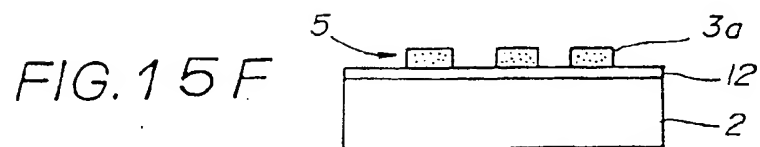
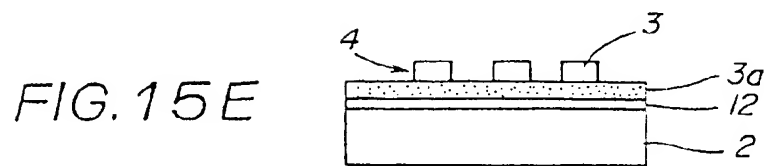
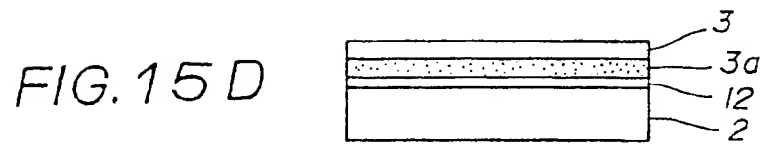
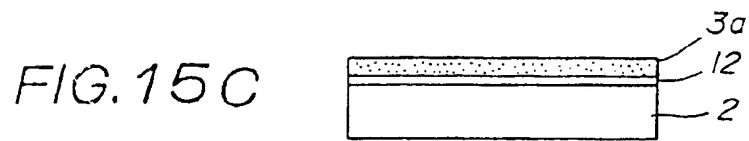


FIG.17 A

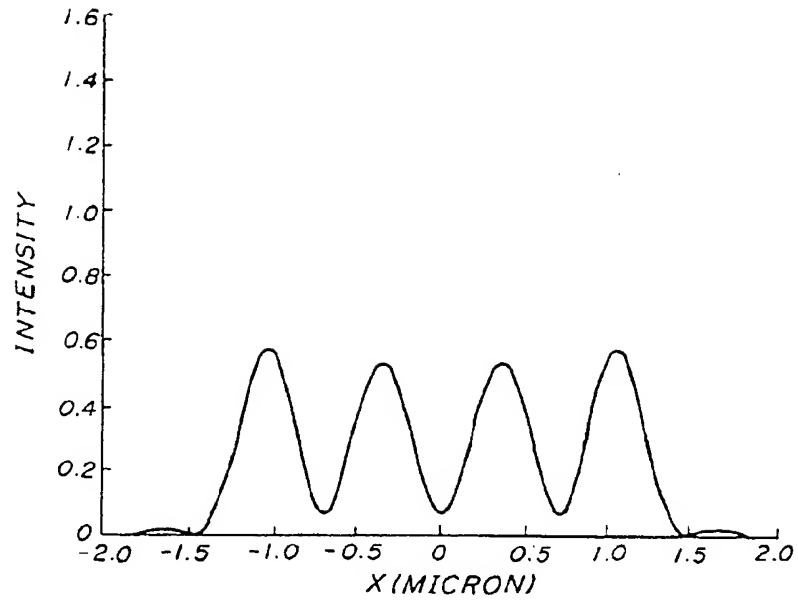


FIG.17 B

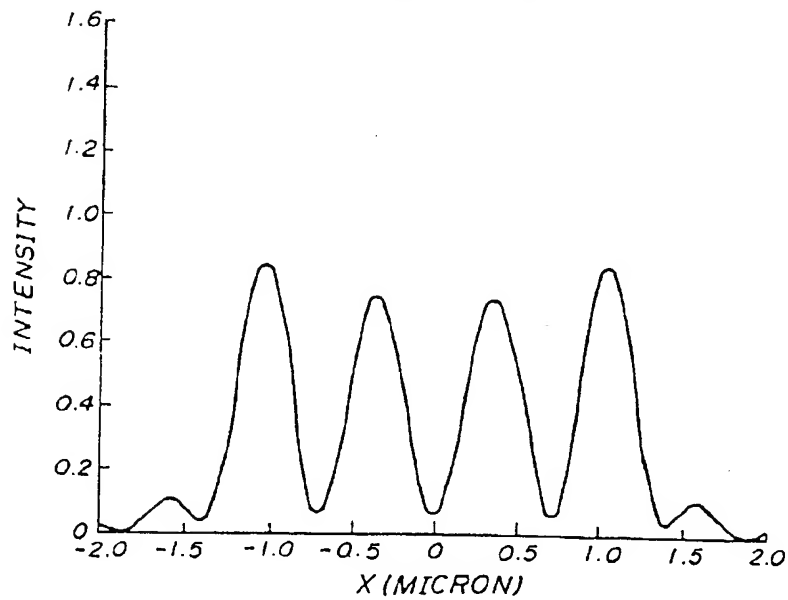


FIG. 16

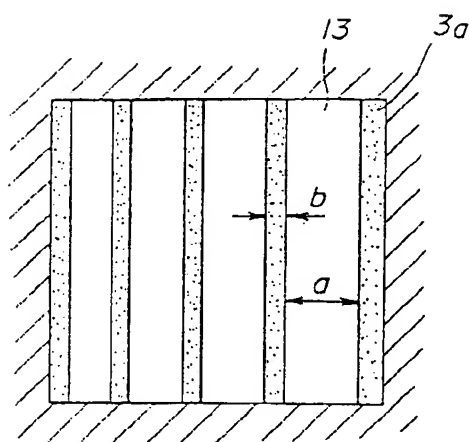


FIG. 18 A

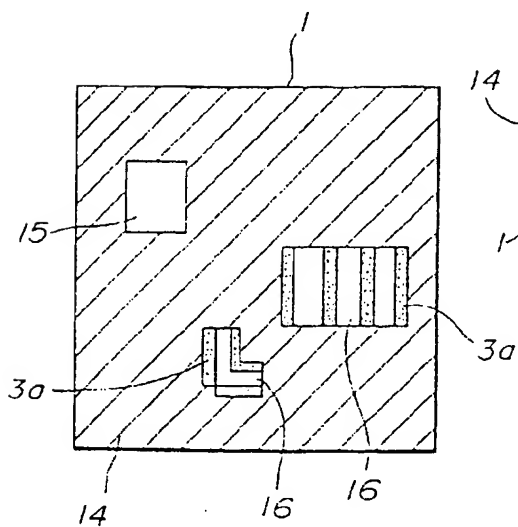


FIG. 18 B

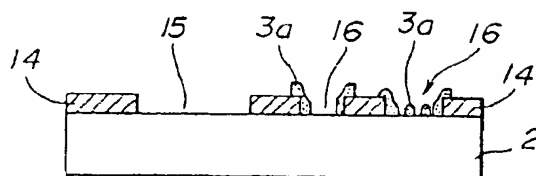


FIG. 18 C

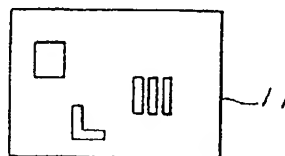




FIG. 19

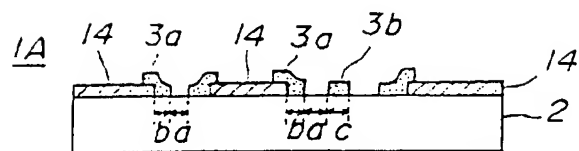


FIG. 22

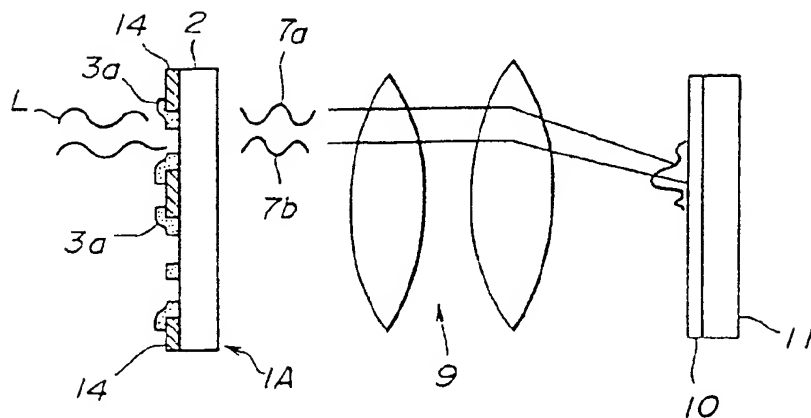


FIG. 23 A

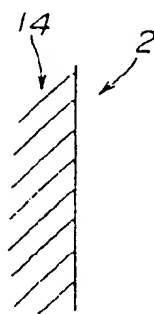


FIG. 23B

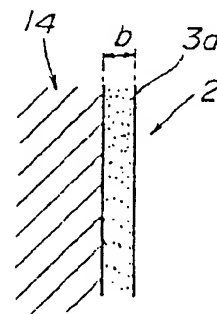


FIG.20A

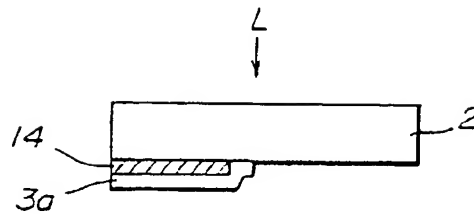


FIG.20B



FIG.21A

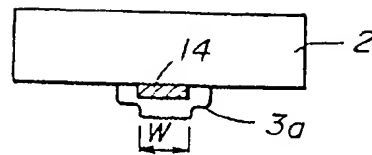


FIG.21B

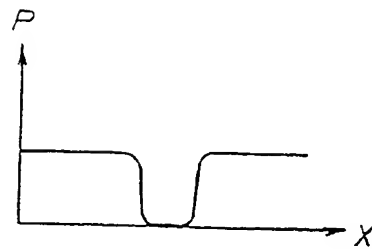


FIG.24A

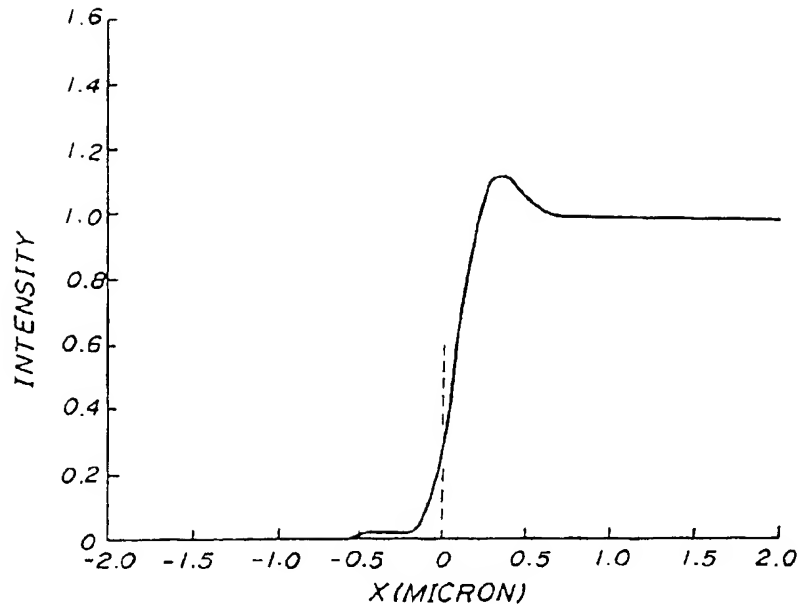


FIG.24B

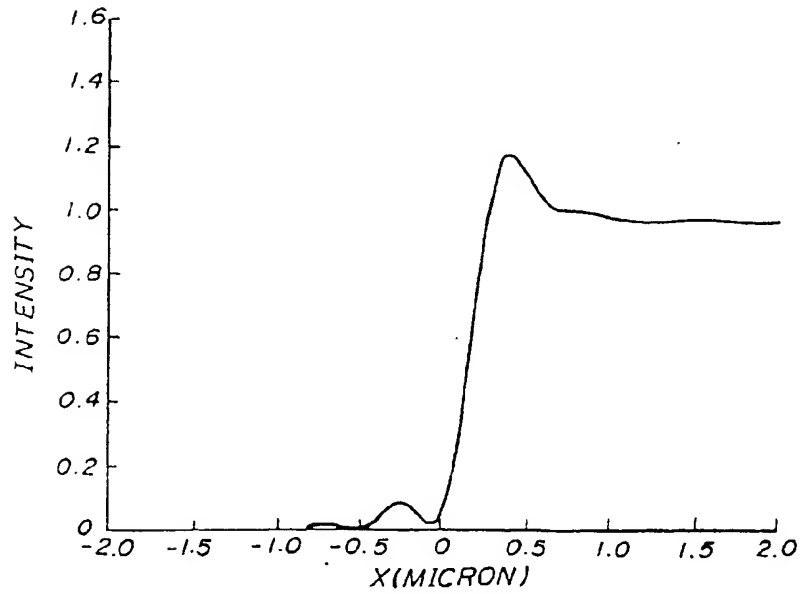


FIG.25

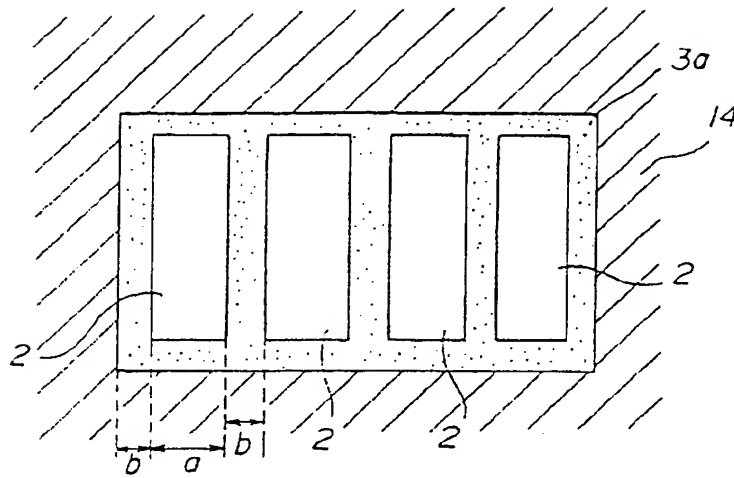


FIG.27

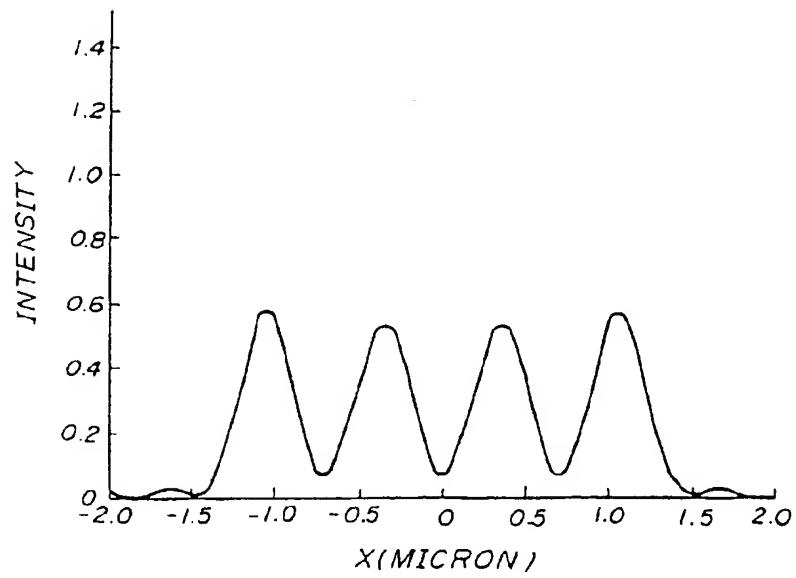


FIG.26A

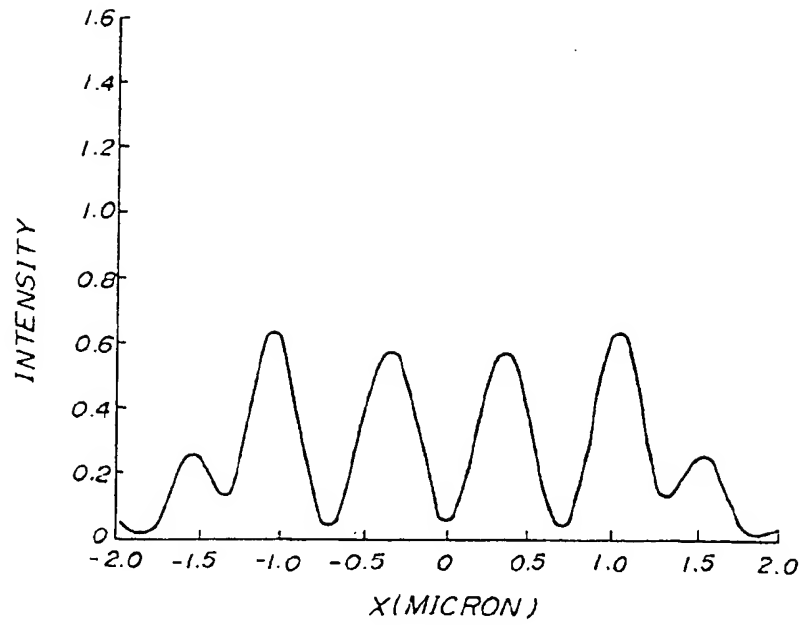


FIG.26B

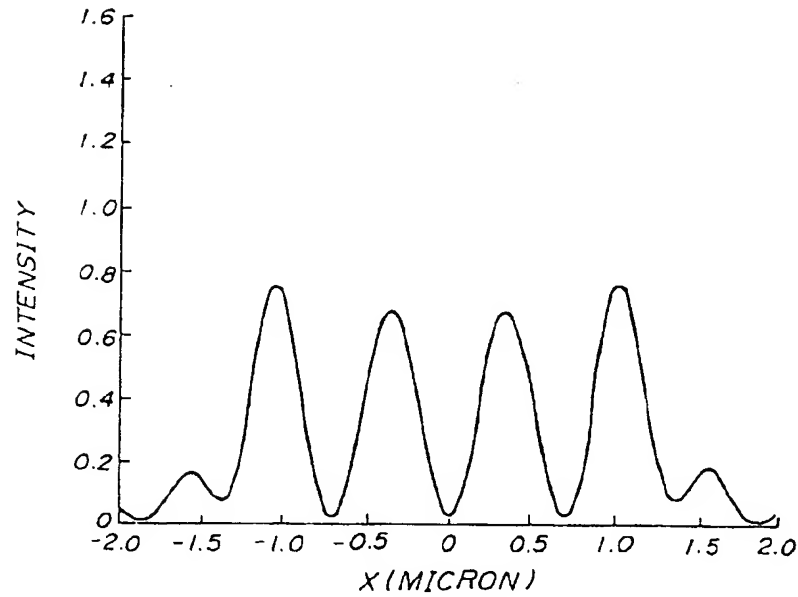


FIG. 26 C

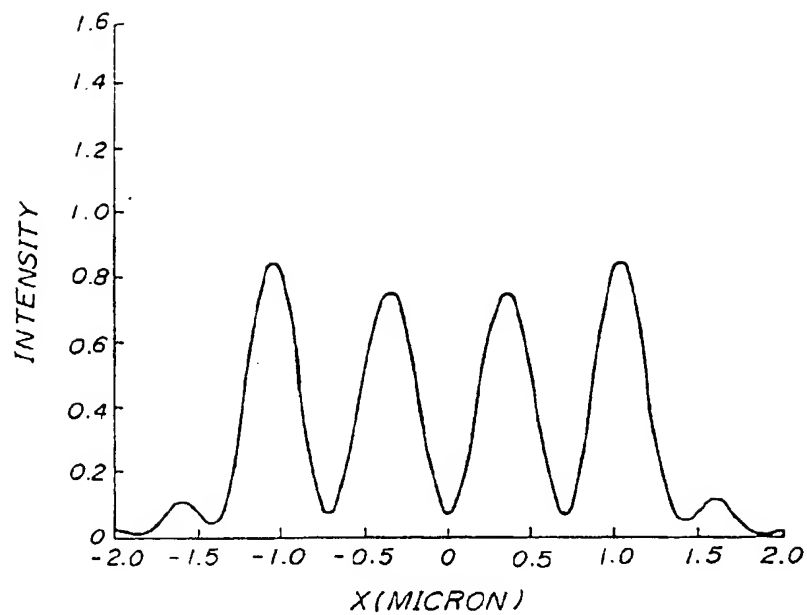


FIG. 26 D

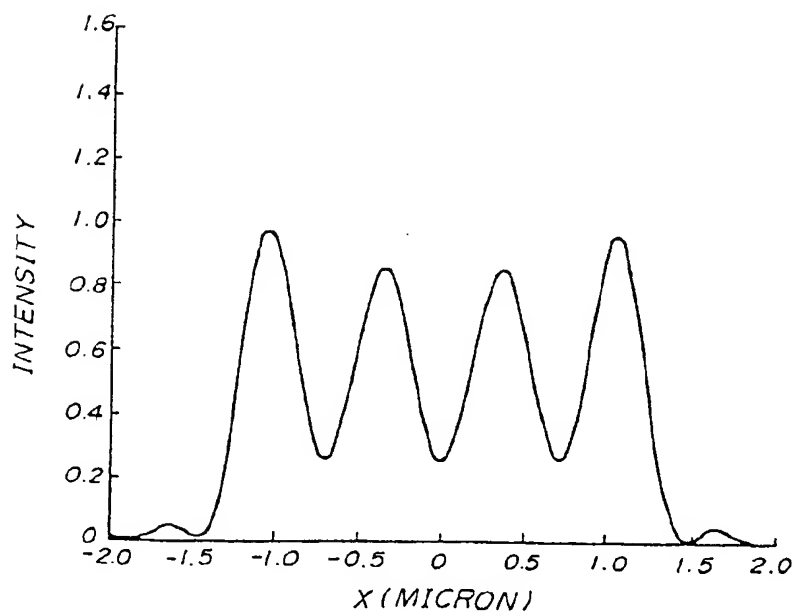


FIG.28A

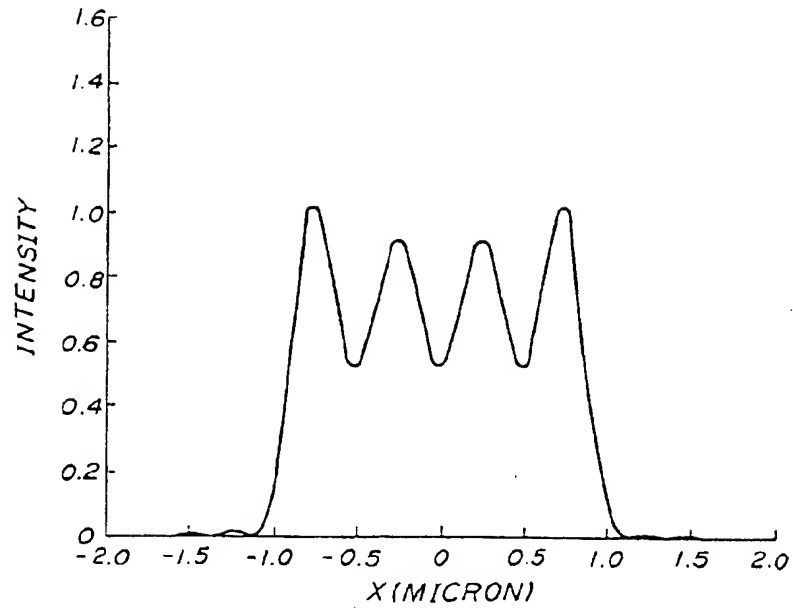


FIG.28B

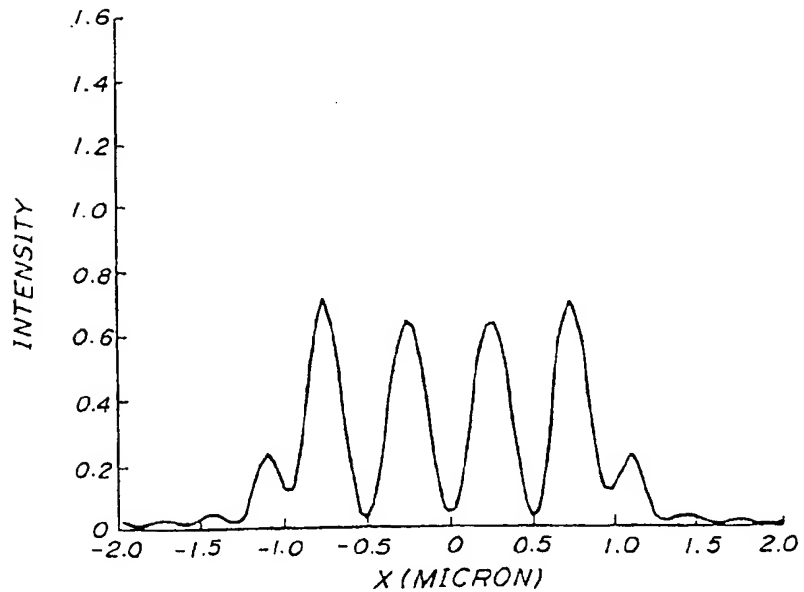


FIG.28C

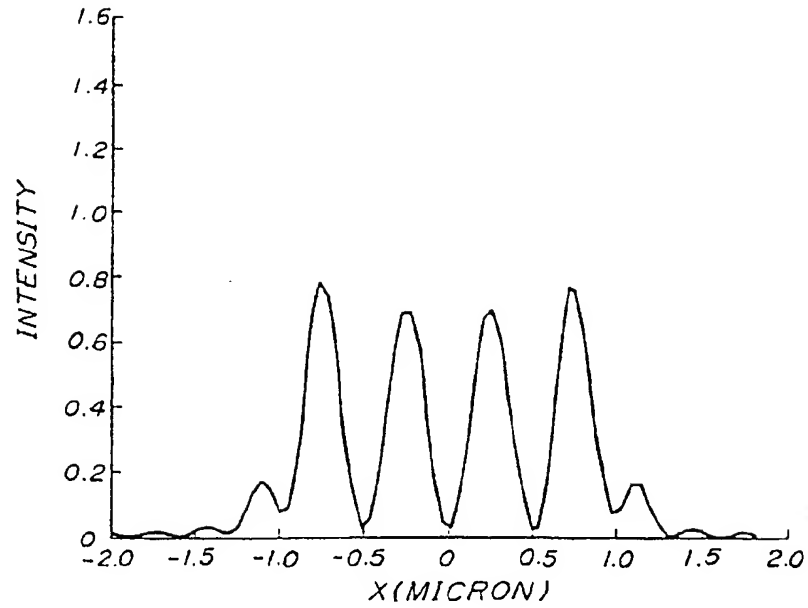


FIG.28D

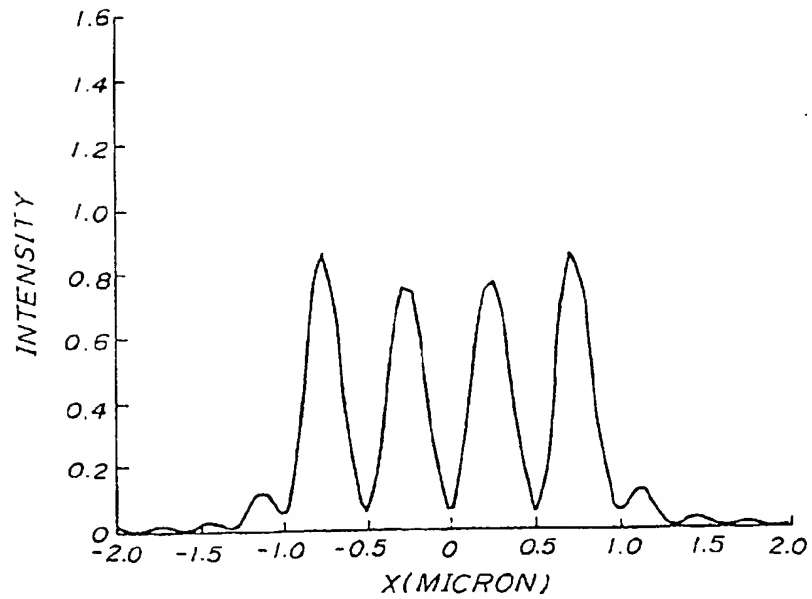




FIG.28E

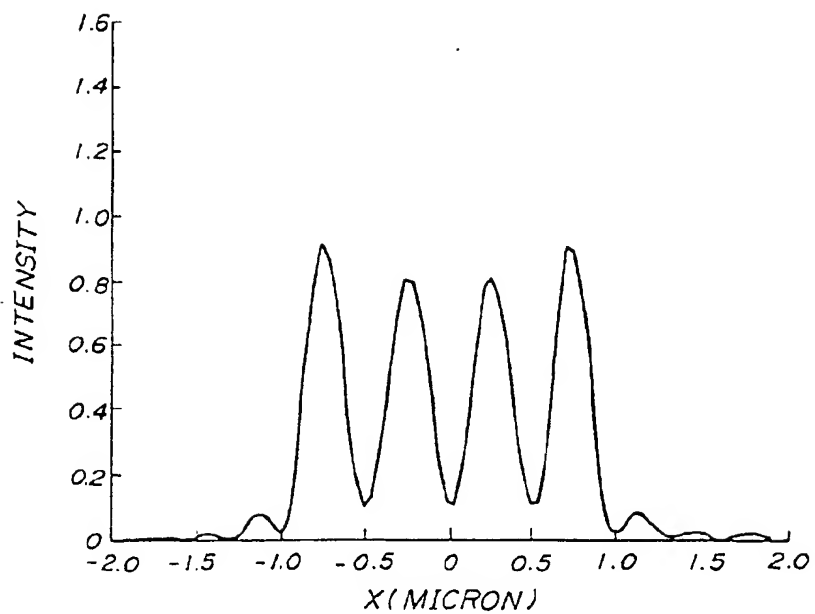


FIG.28F

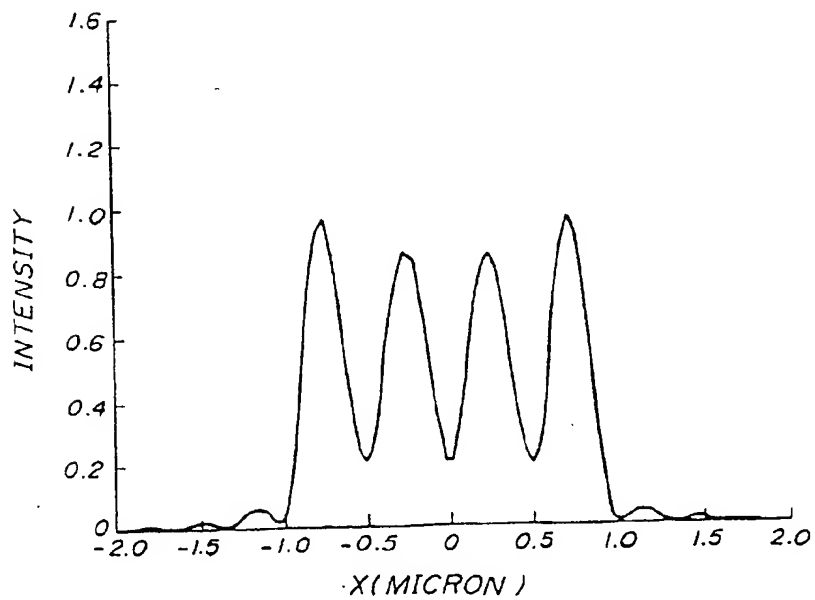


FIG.29 A

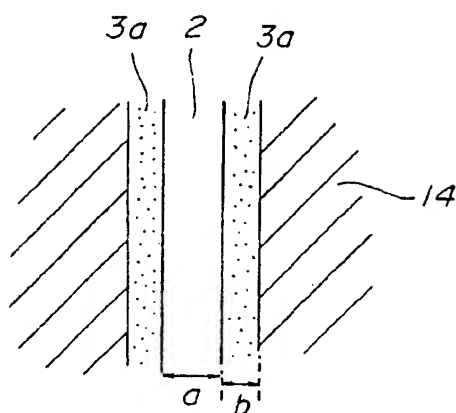


FIG.29B

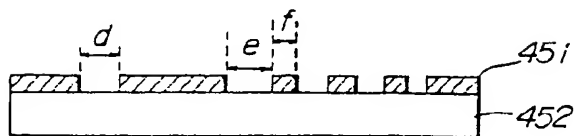


FIG.30A

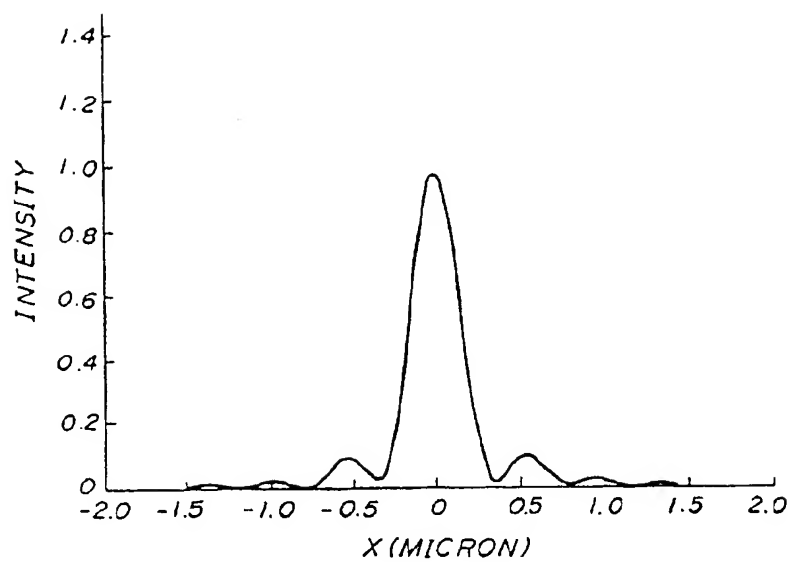


FIG.30B

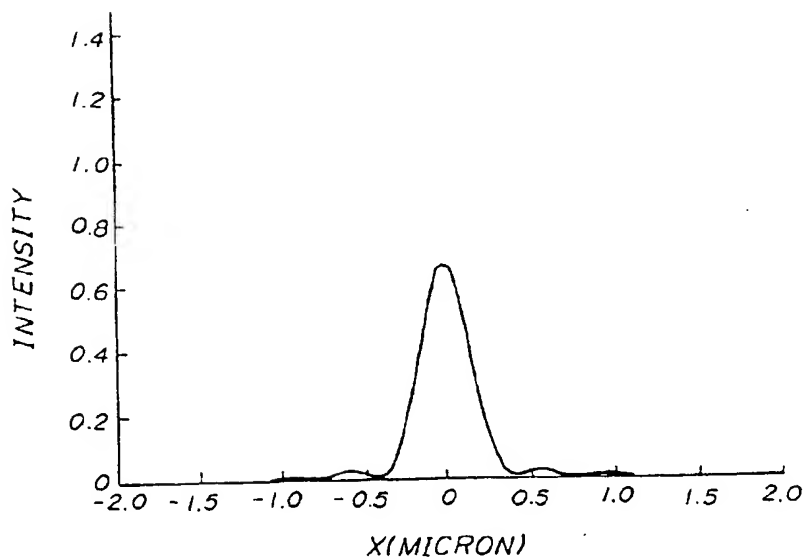


FIG.31A

FIG.31B

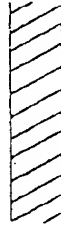
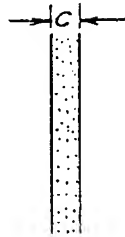


FIG.33A

FIG.33B

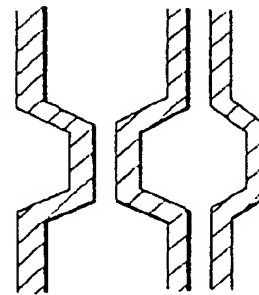
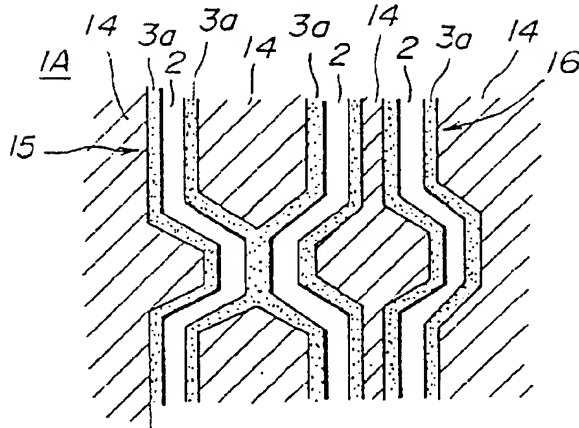


FIG.34A

FIG.34B

FIG.34C

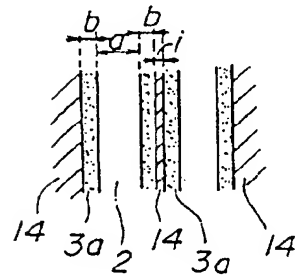
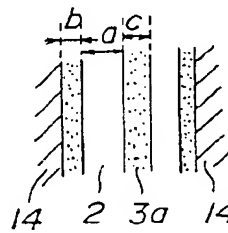
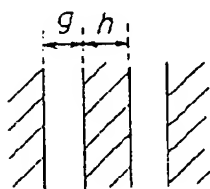


FIG.32A

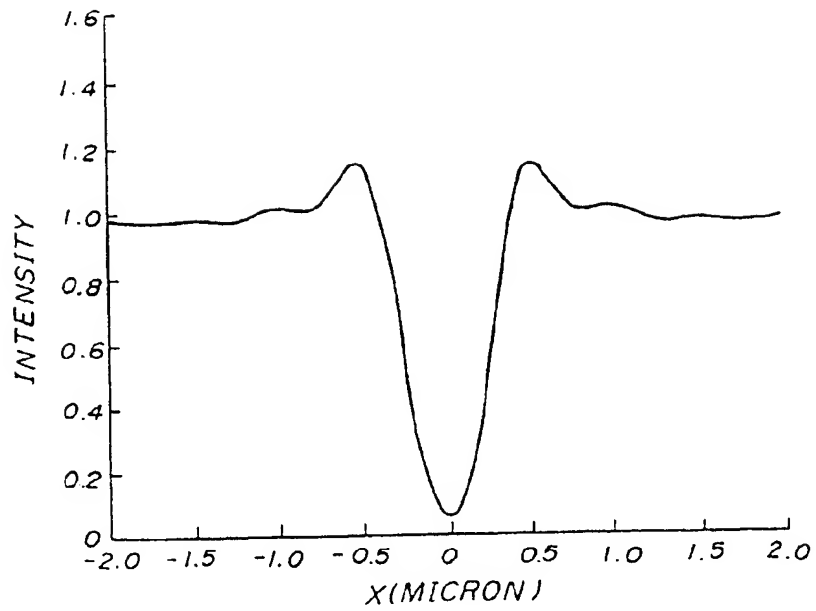


FIG.32B

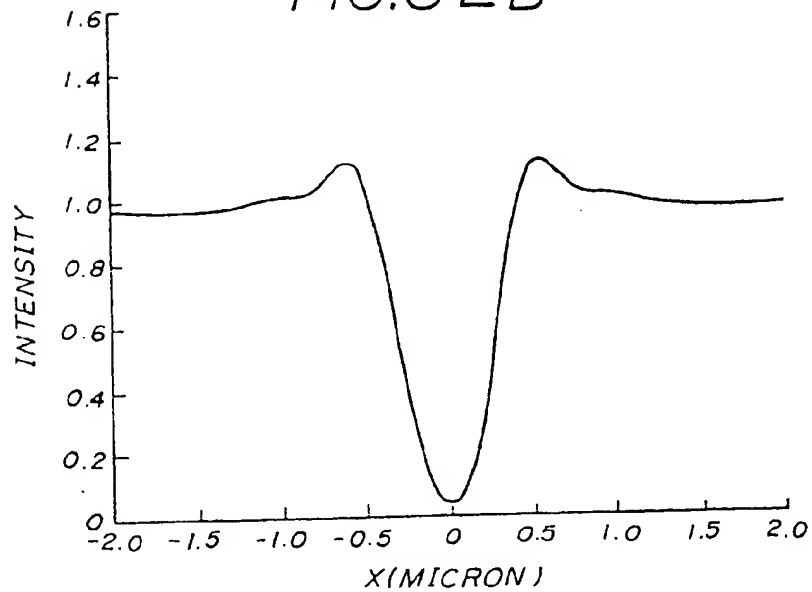


FIG.35A

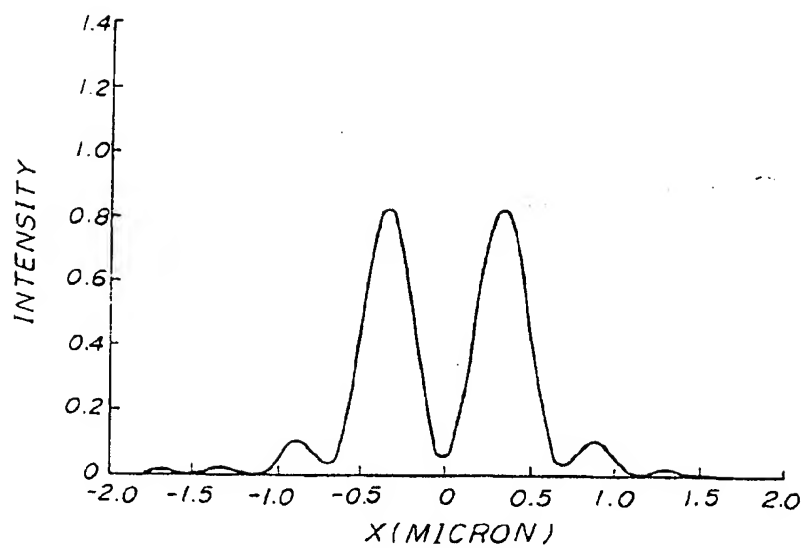


FIG.35B

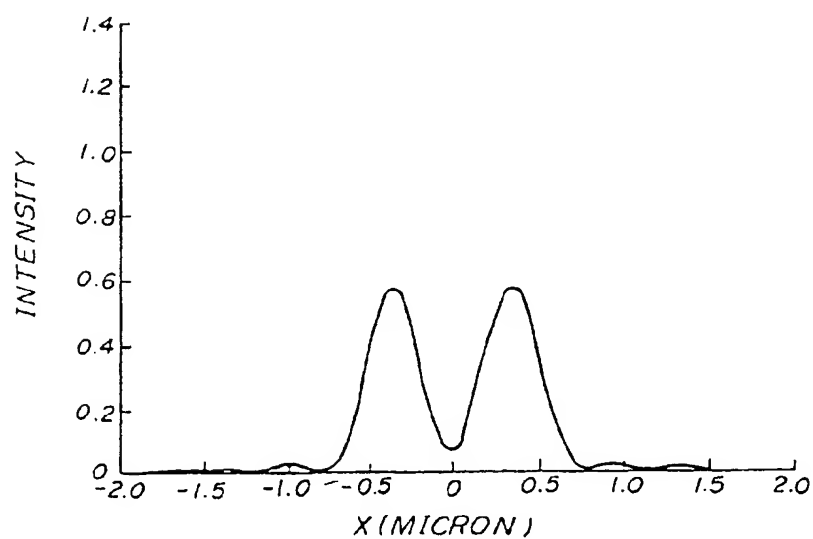


FIG.36

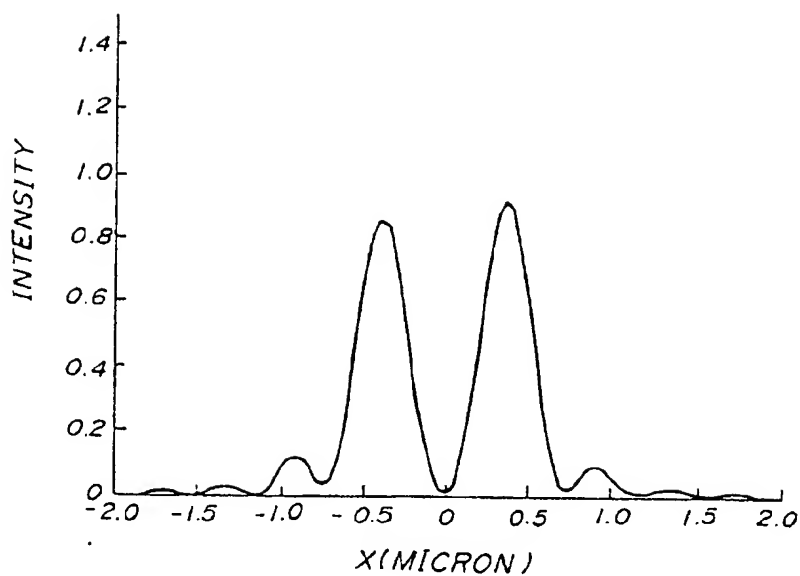


FIG.37

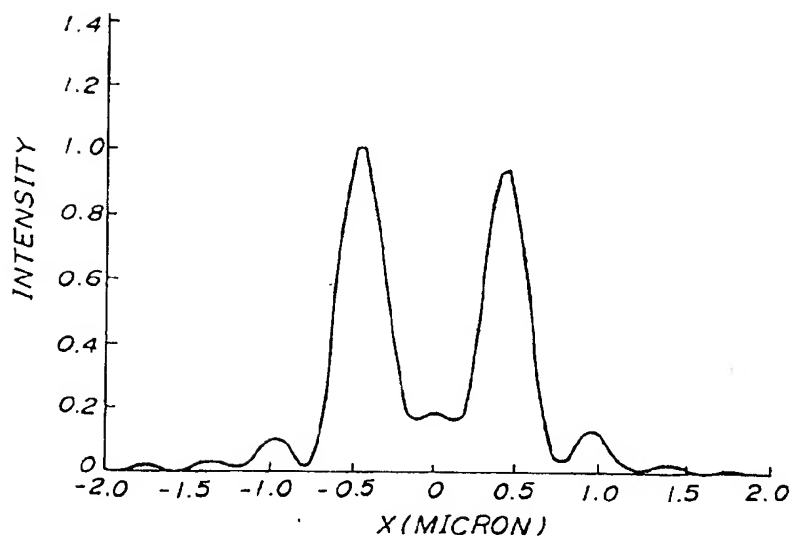


FIG.38

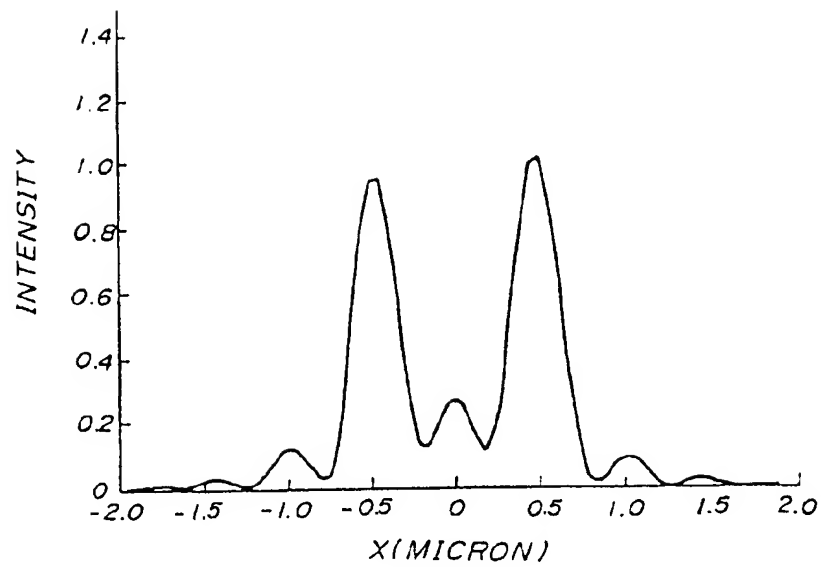


FIG.39

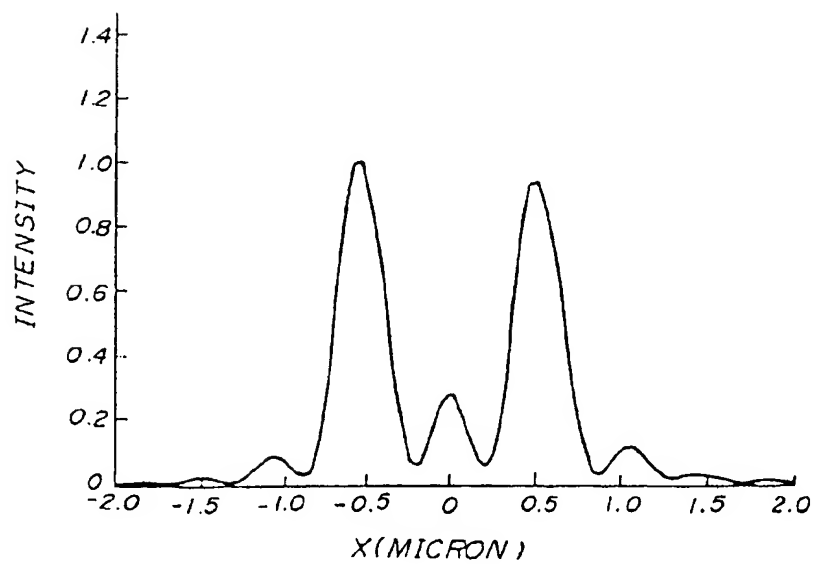




FIG.40

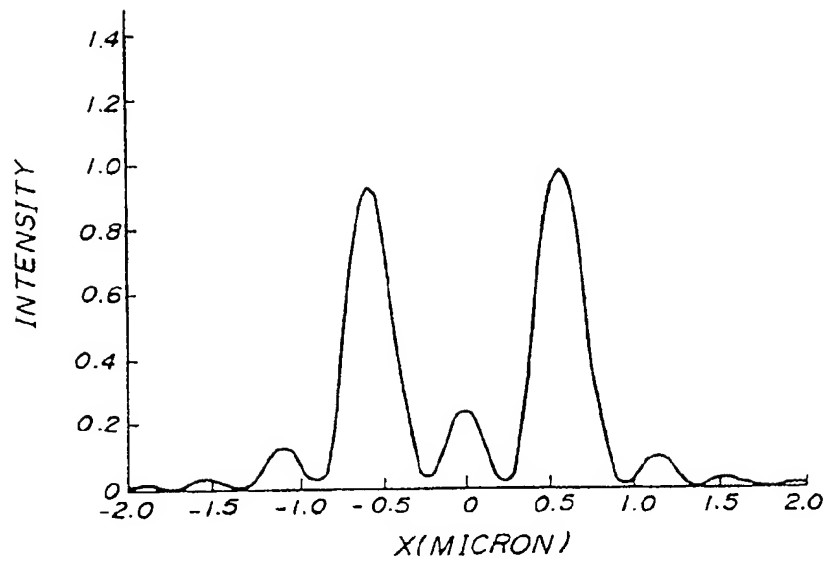


FIG.41

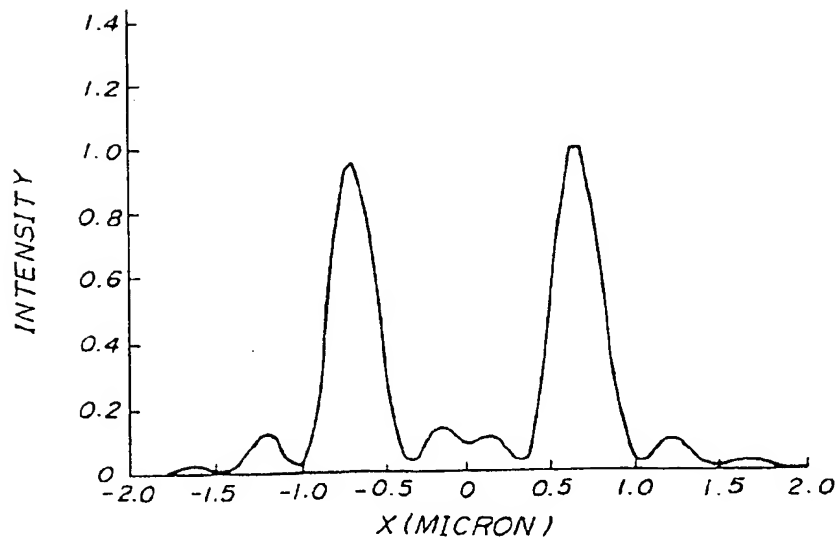


FIG.42A

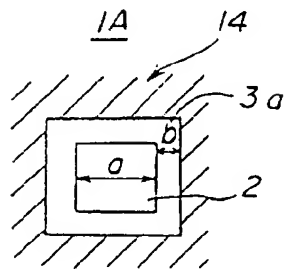


FIG.42B

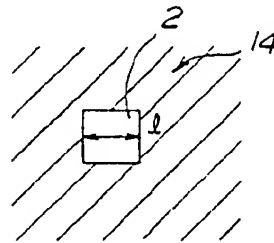


FIG.43A

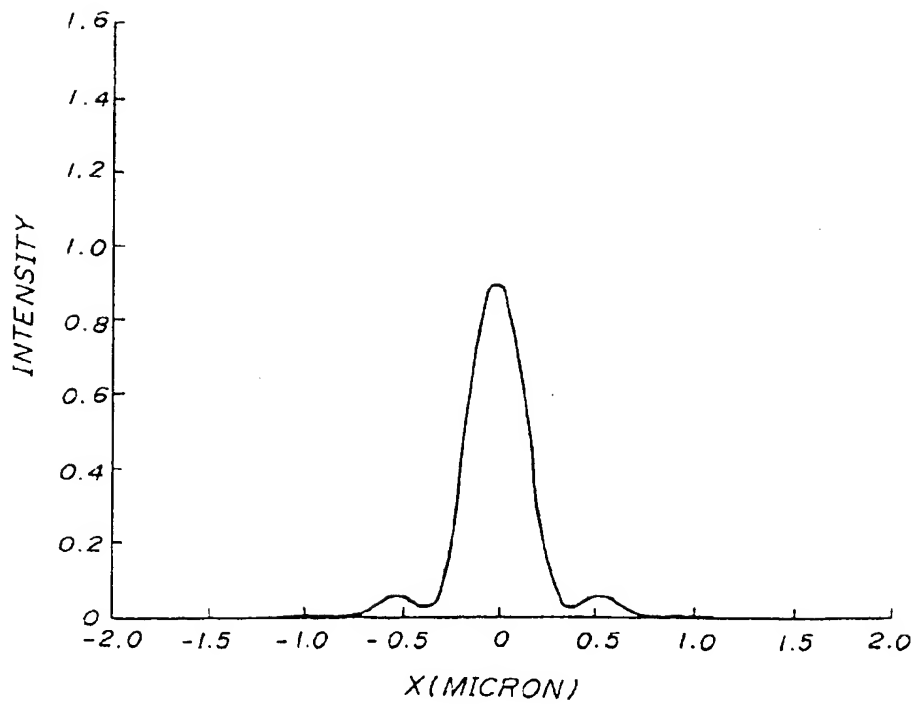
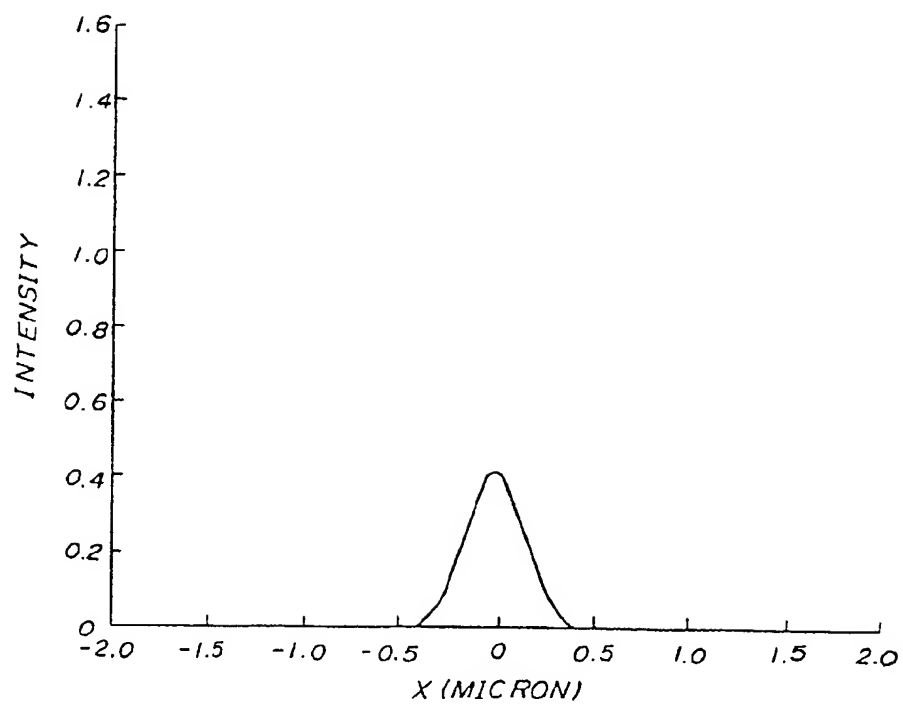
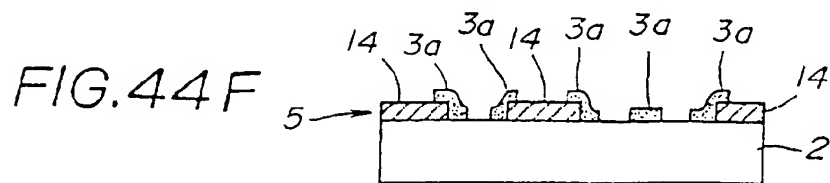
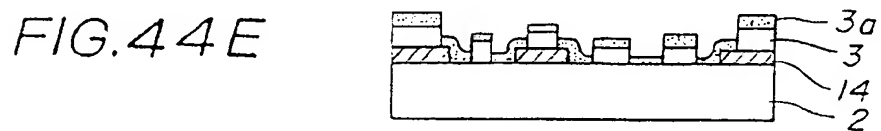
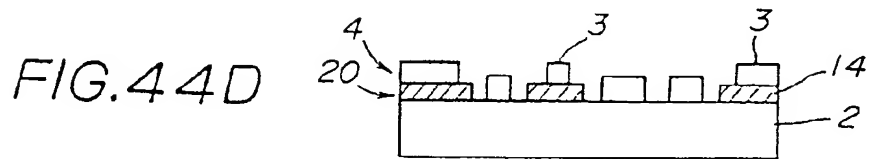
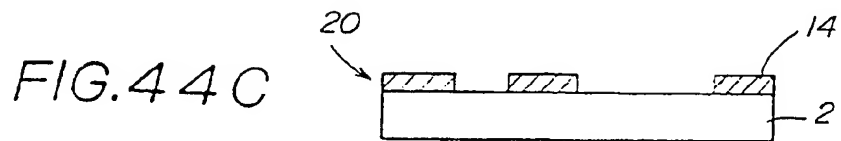
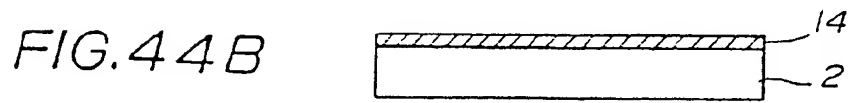
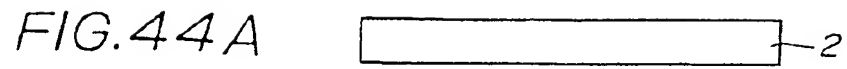


FIG. 43B





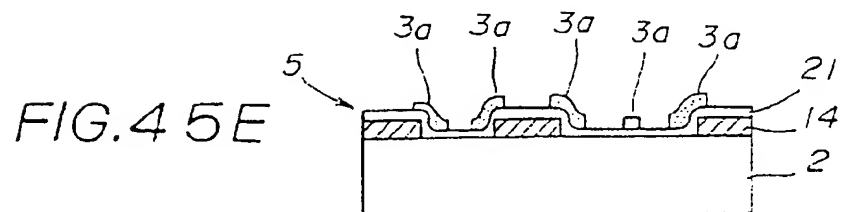
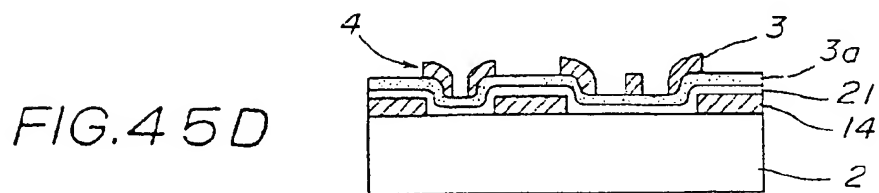
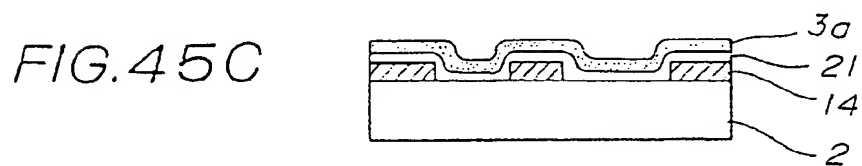
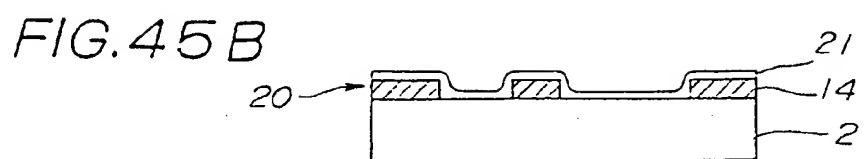
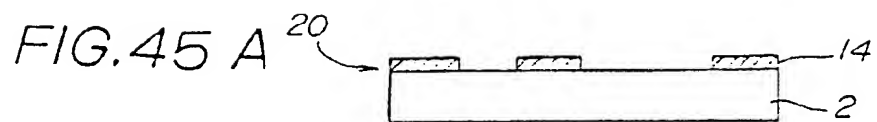


FIG. 46 A

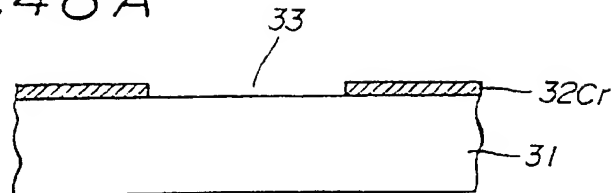


FIG. 46 B

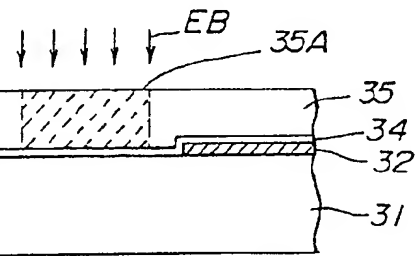


FIG. 46 C

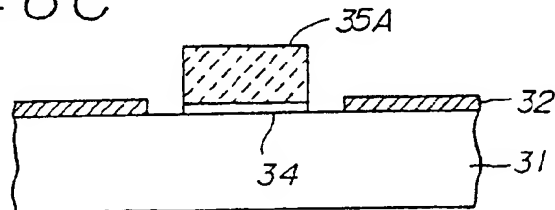


FIG. 46 D

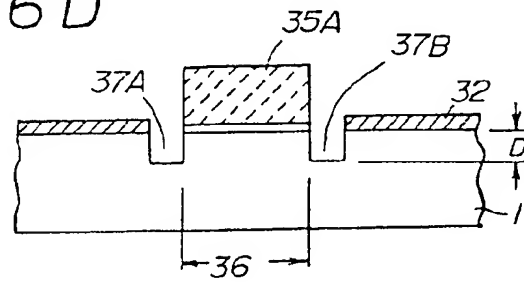


FIG. 46E

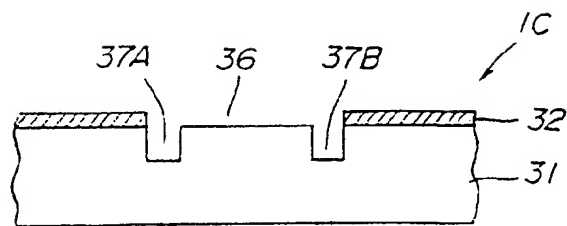


FIG. 47

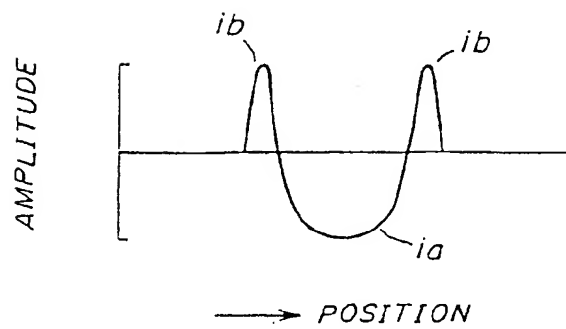


FIG.48A

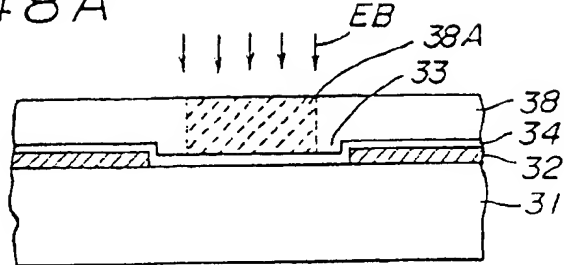


FIG.48B

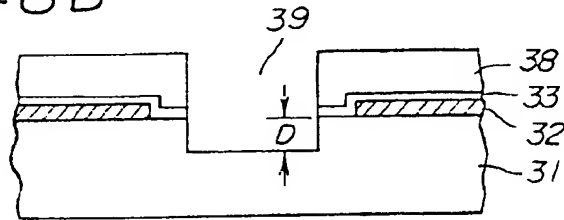


FIG.48C

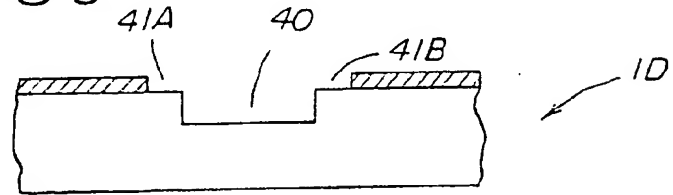


FIG.49

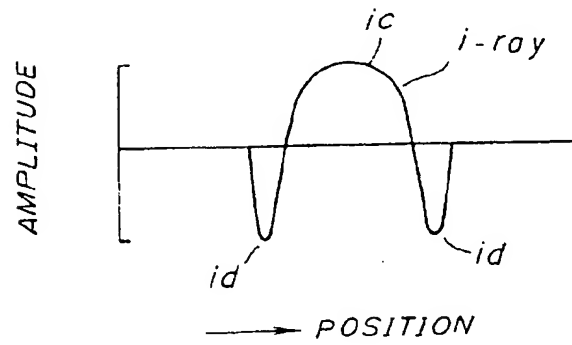




FIG. 50A

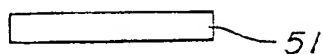


FIG. 50B



FIG. 50C

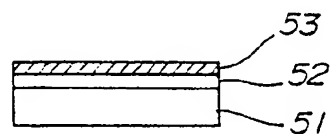


FIG. 50D

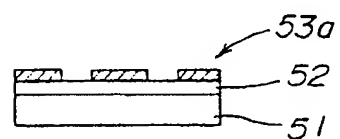


FIG. 50E

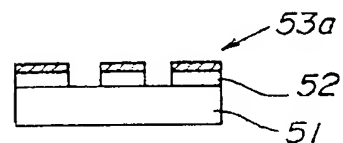


FIG. 50F

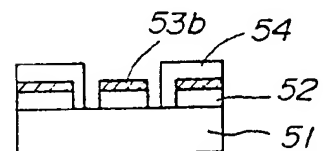


FIG. 50G

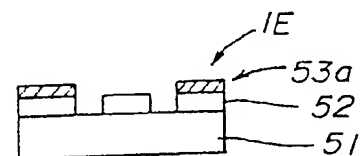
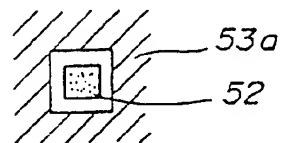
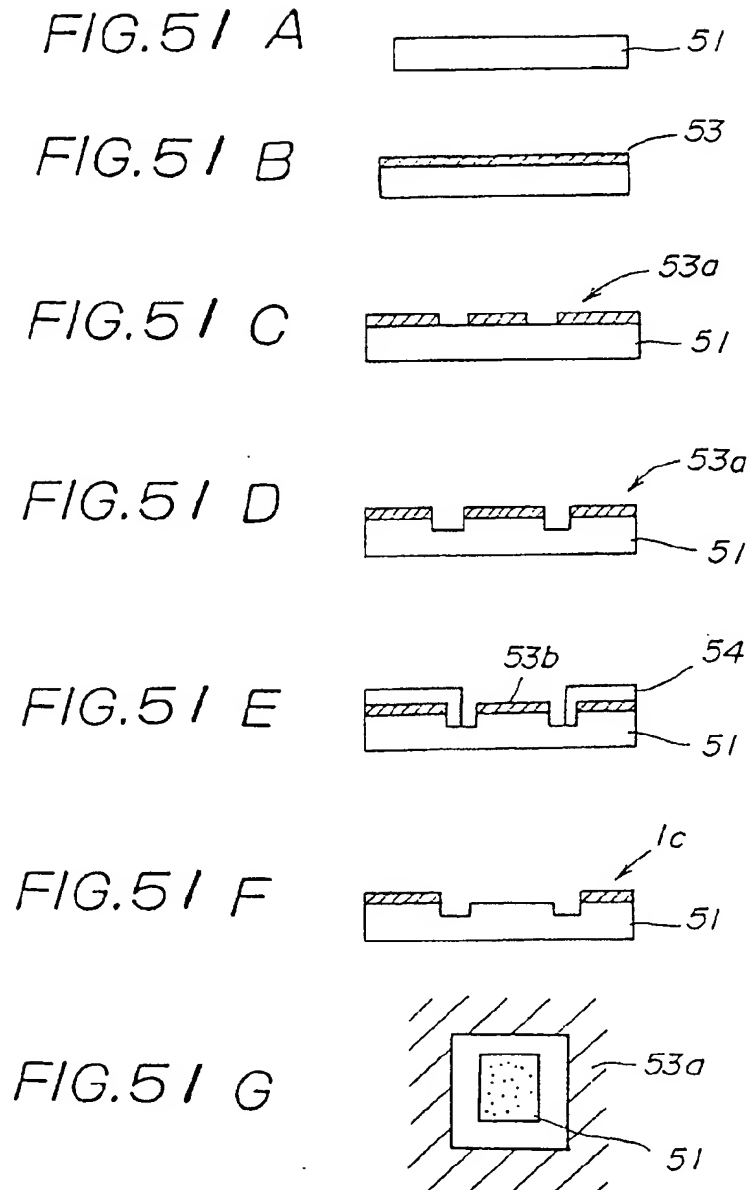


FIG. 50H





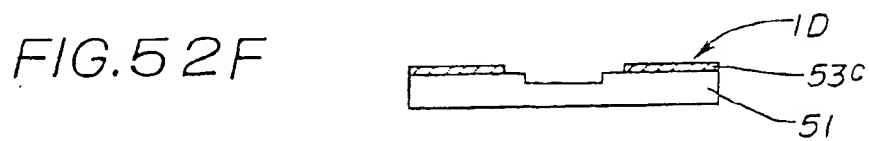
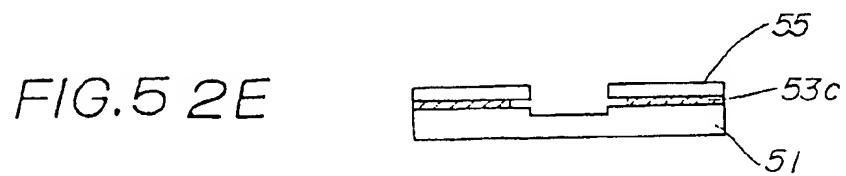
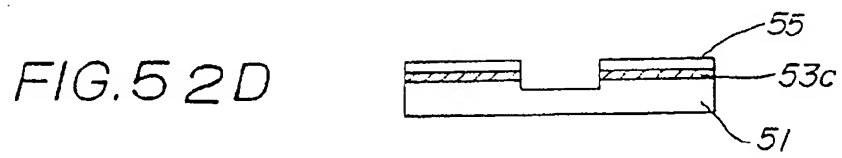
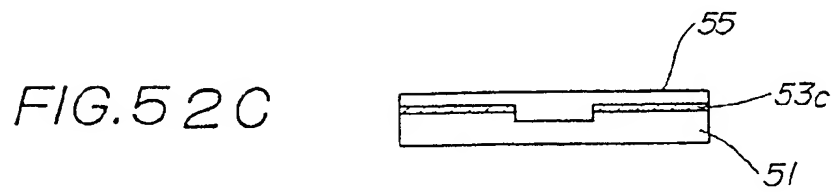
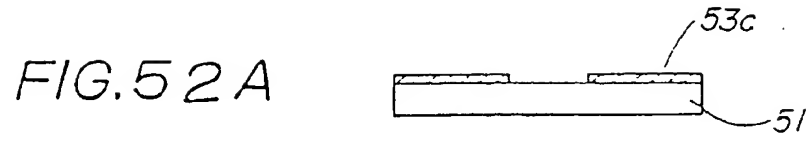


FIG.53A

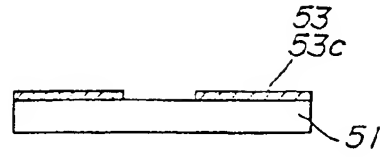


FIG.53B

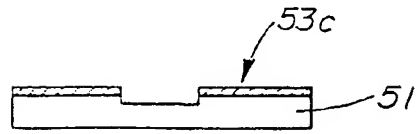


FIG.53C

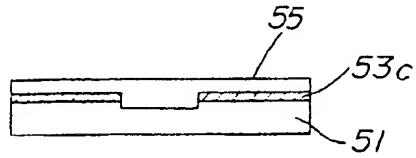


FIG.53D

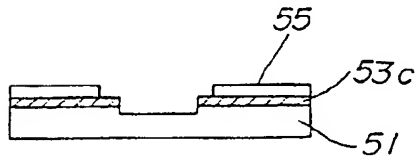


FIG.53E

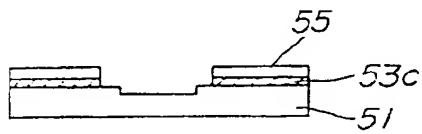
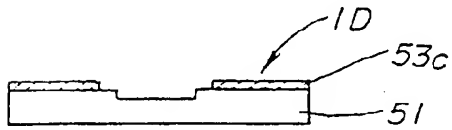


FIG.53F



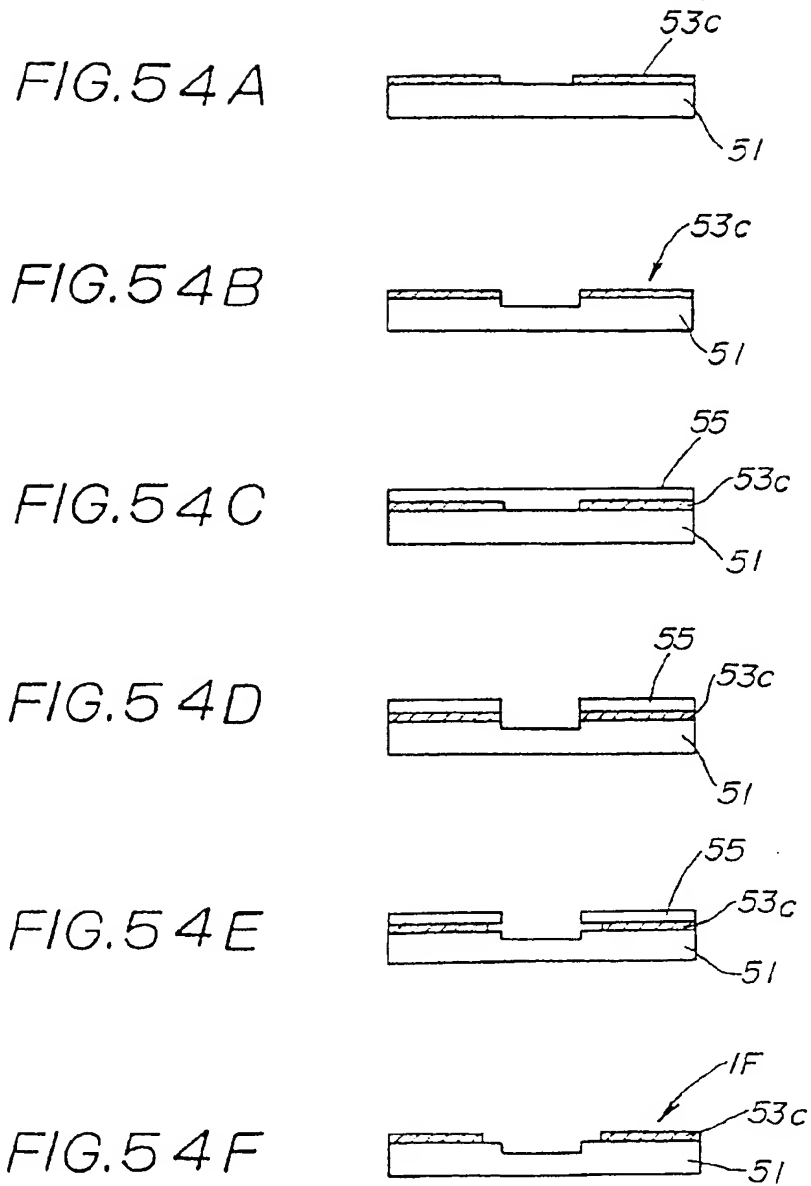


FIG. 55 A

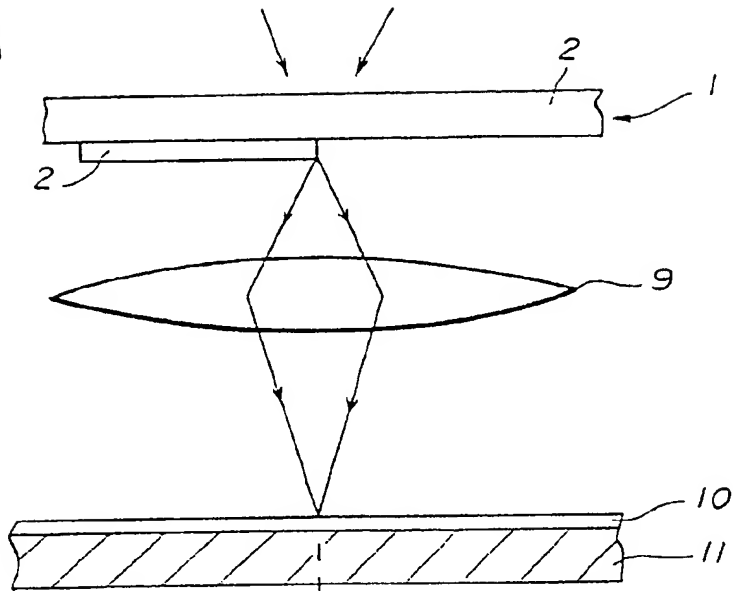


FIG. 55 B

ELECTRICAL  
VECTOR OF  
LIGHT  $E$

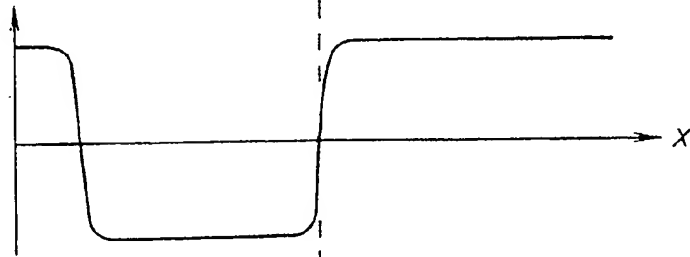


FIG. 55 C

LIGHT  
INTENSITY  $P$

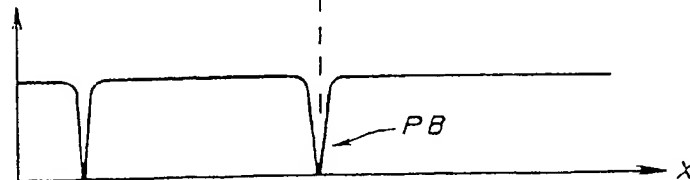


FIG.56 A

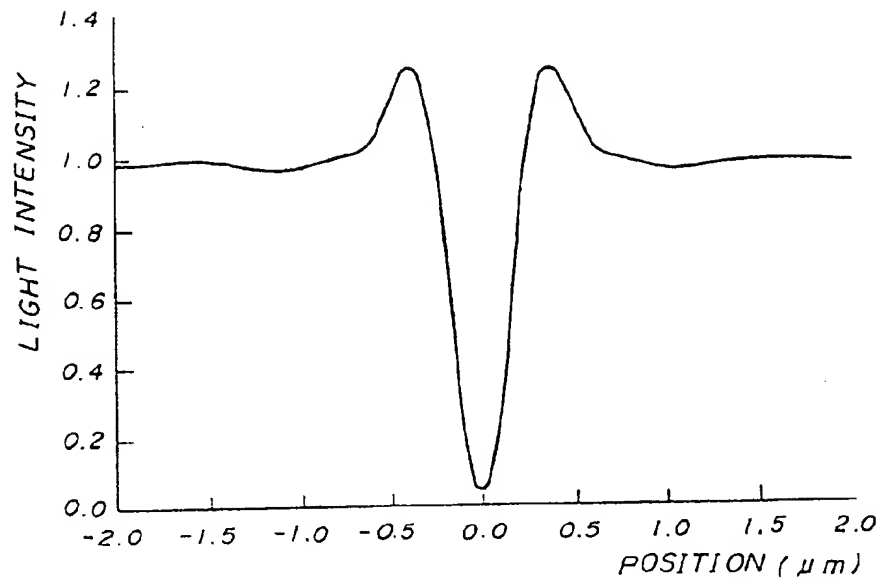


FIG.56 B

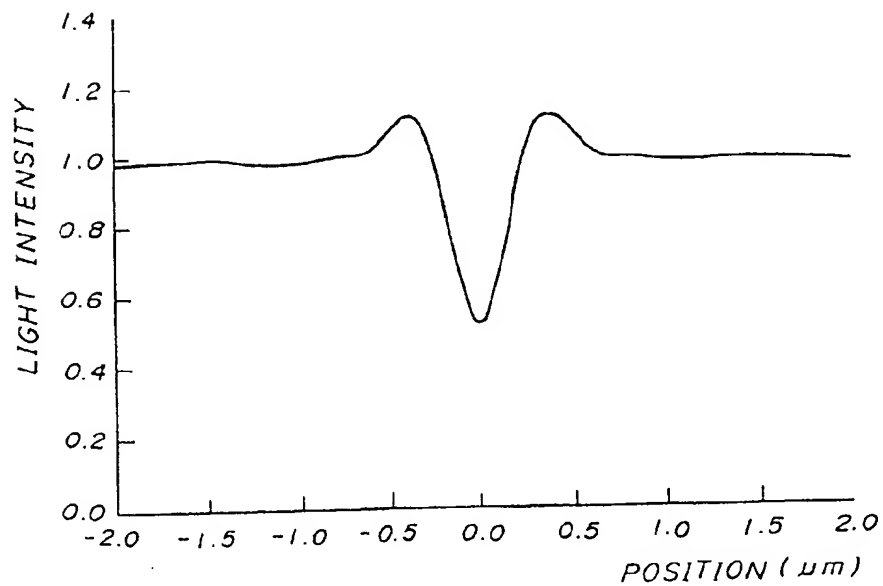


FIG.57 A

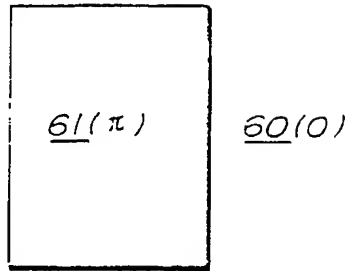


FIG.57 B

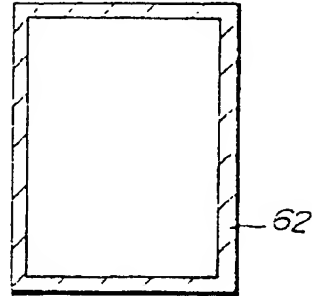


FIG.58 A

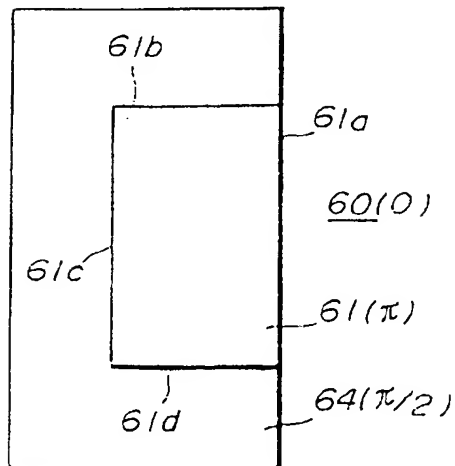


FIG.58 B

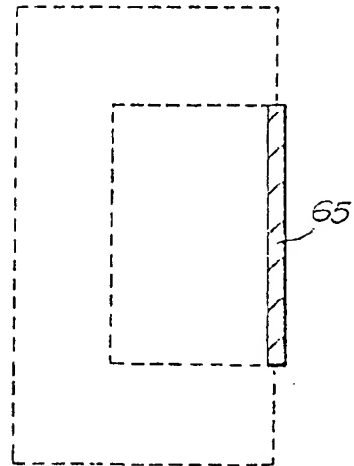




FIG.59 A

FIG.59 B

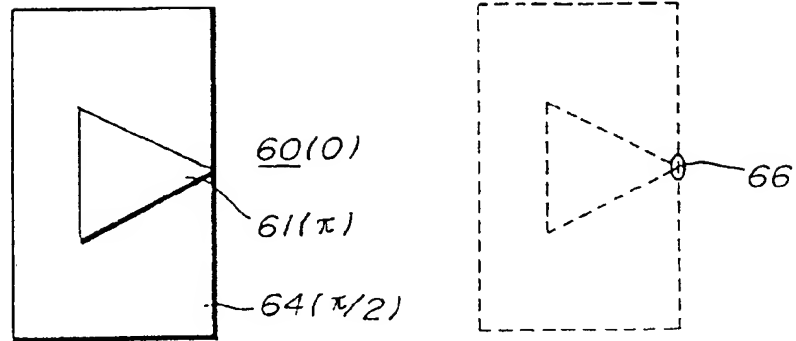


FIG.60A

FIG.60B

FIG.60C

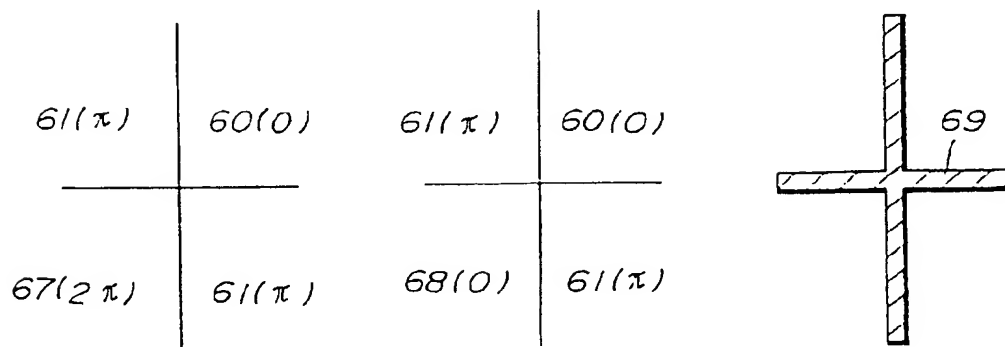


FIG. 61 A

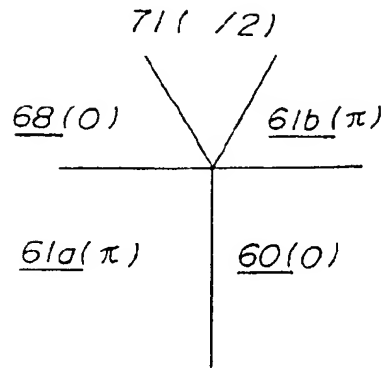


FIG. 61 B

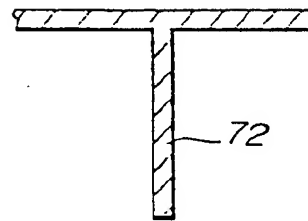


FIG. 62 A

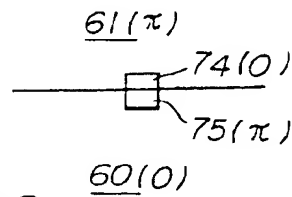


FIG. 62 B

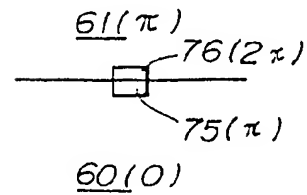


FIG. 62 C

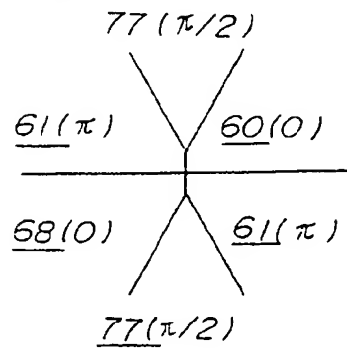


FIG. 62 D



FIG. 63 A

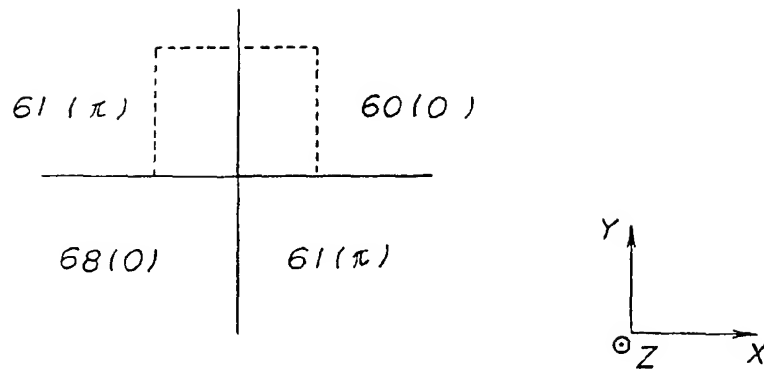


FIG. 63 B

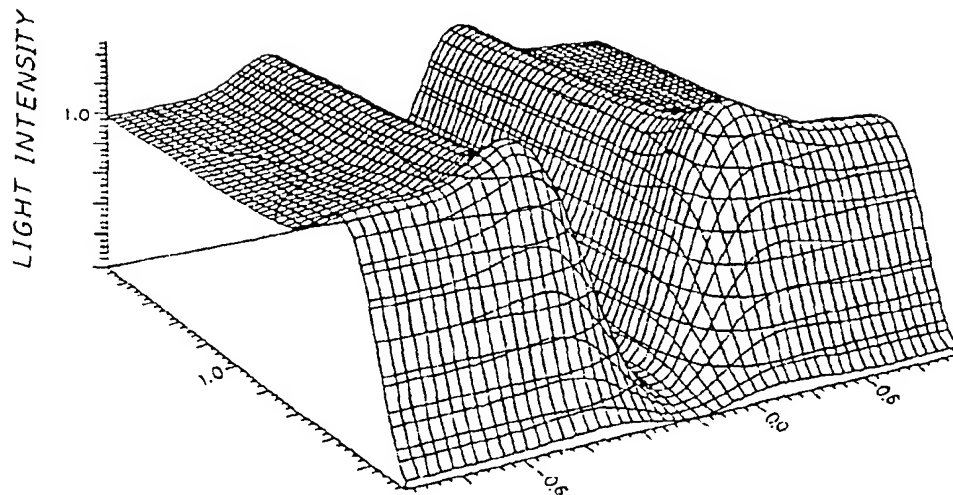


FIG. 63 C

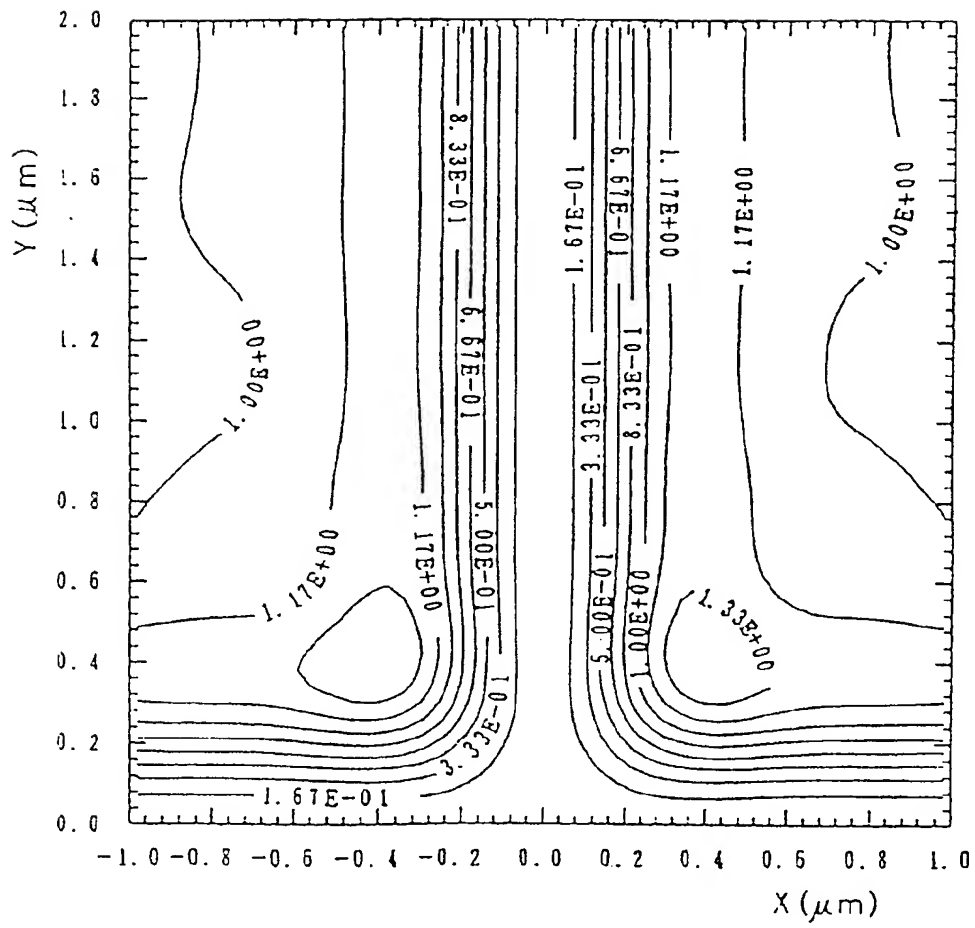


FIG. 64 A

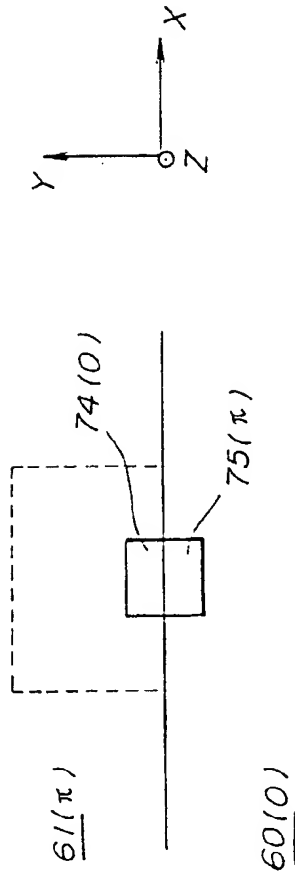


FIG. 64 B

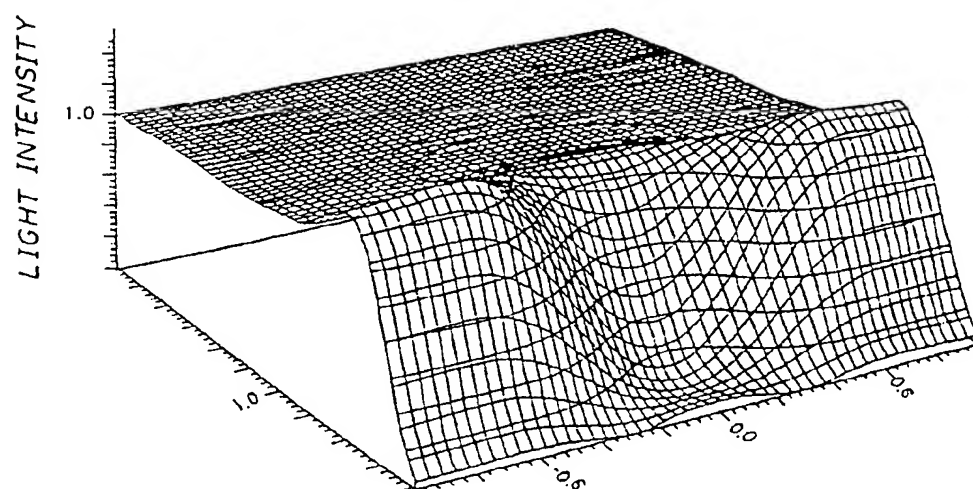


FIG. 64 C

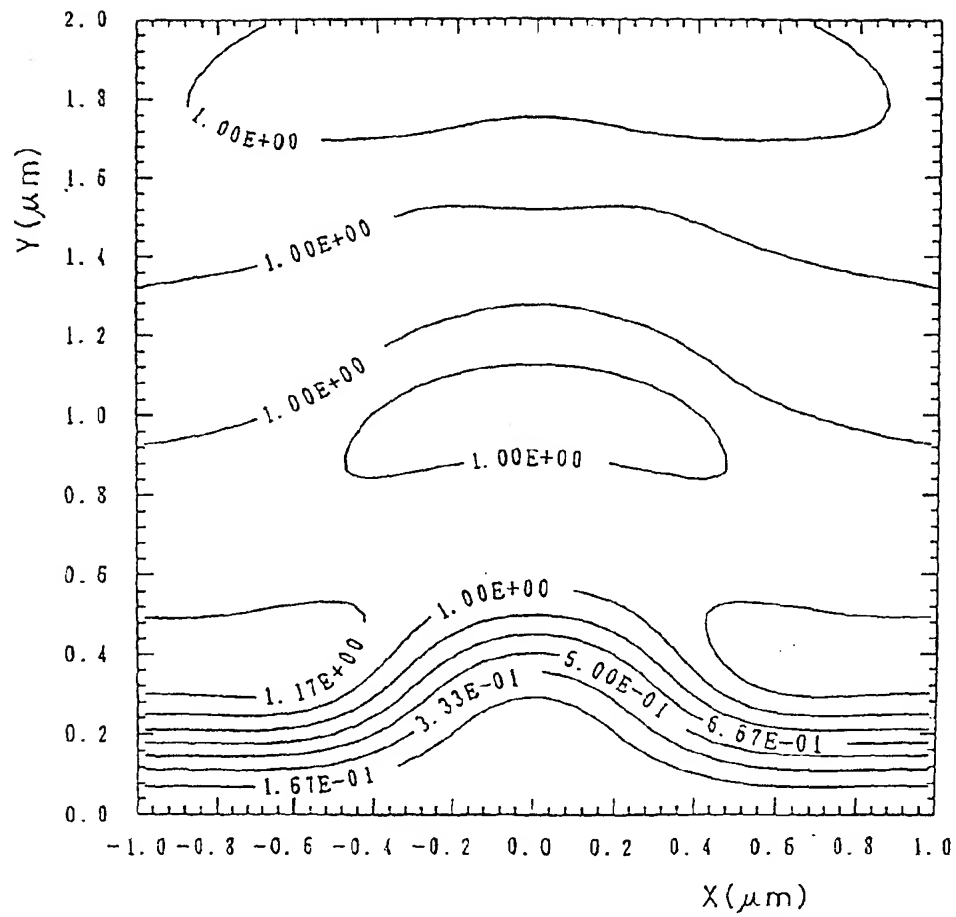


FIG. 65 A

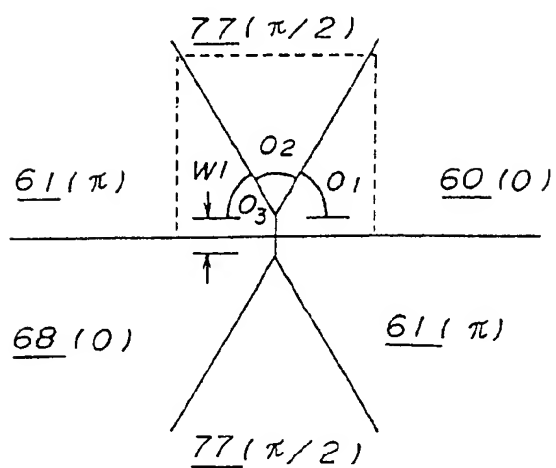


FIG. 65 B

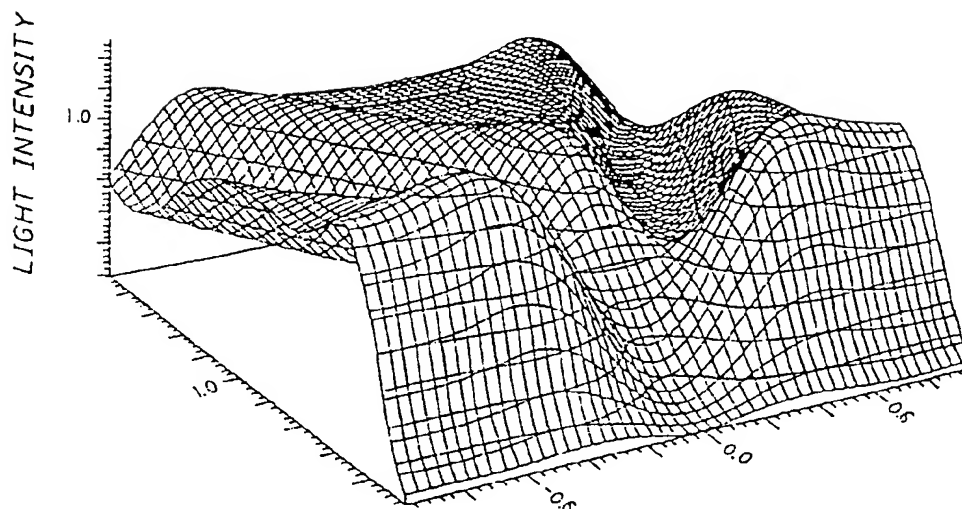




FIG. 65 C

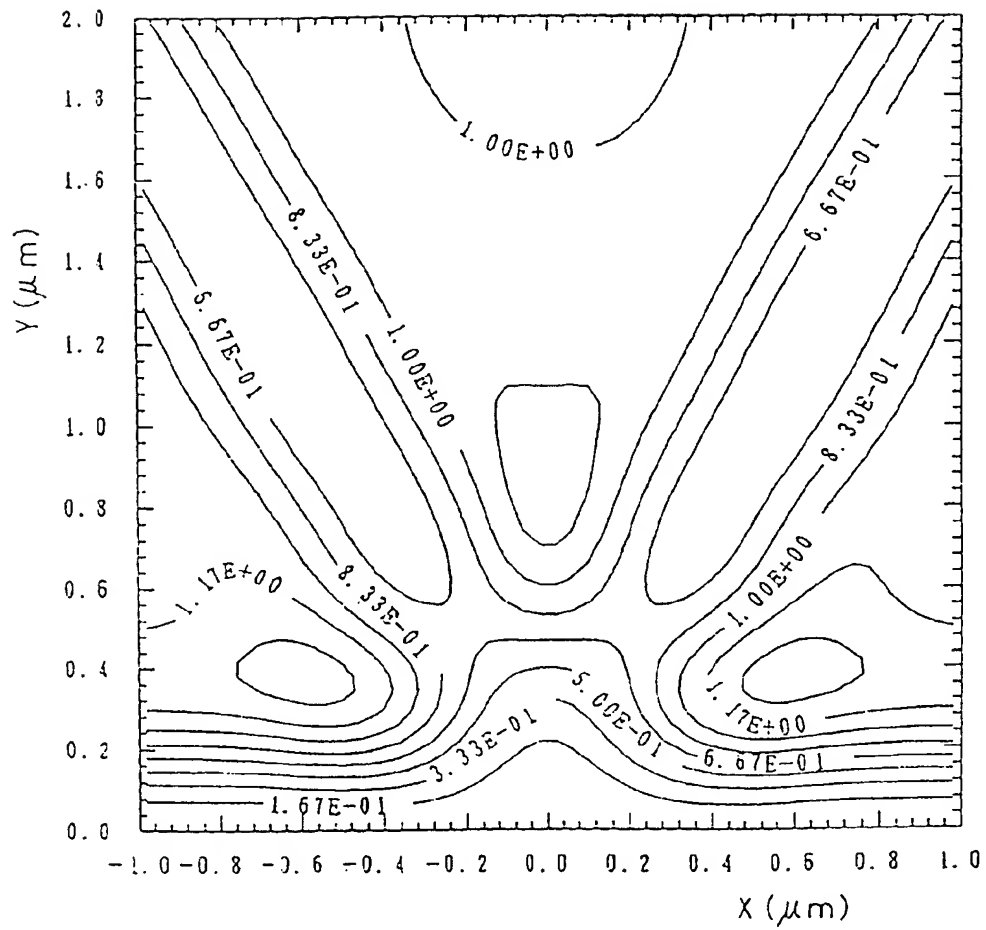


FIG. 66A

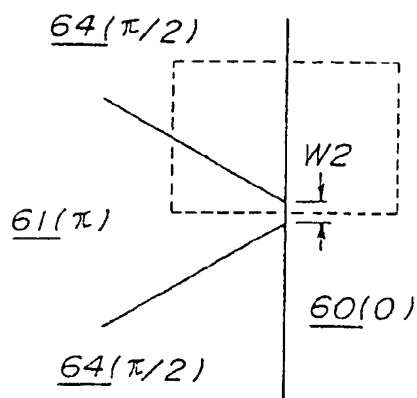


FIG. 66 B

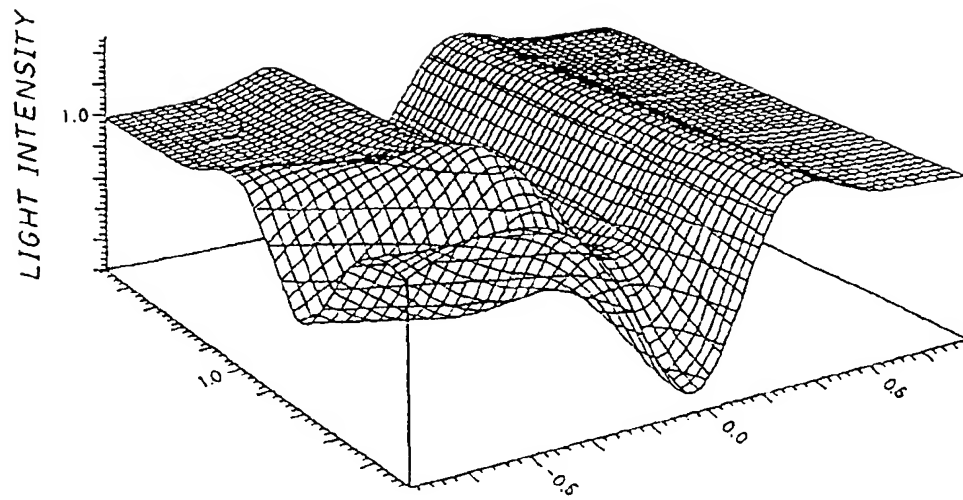


FIG. 66 C

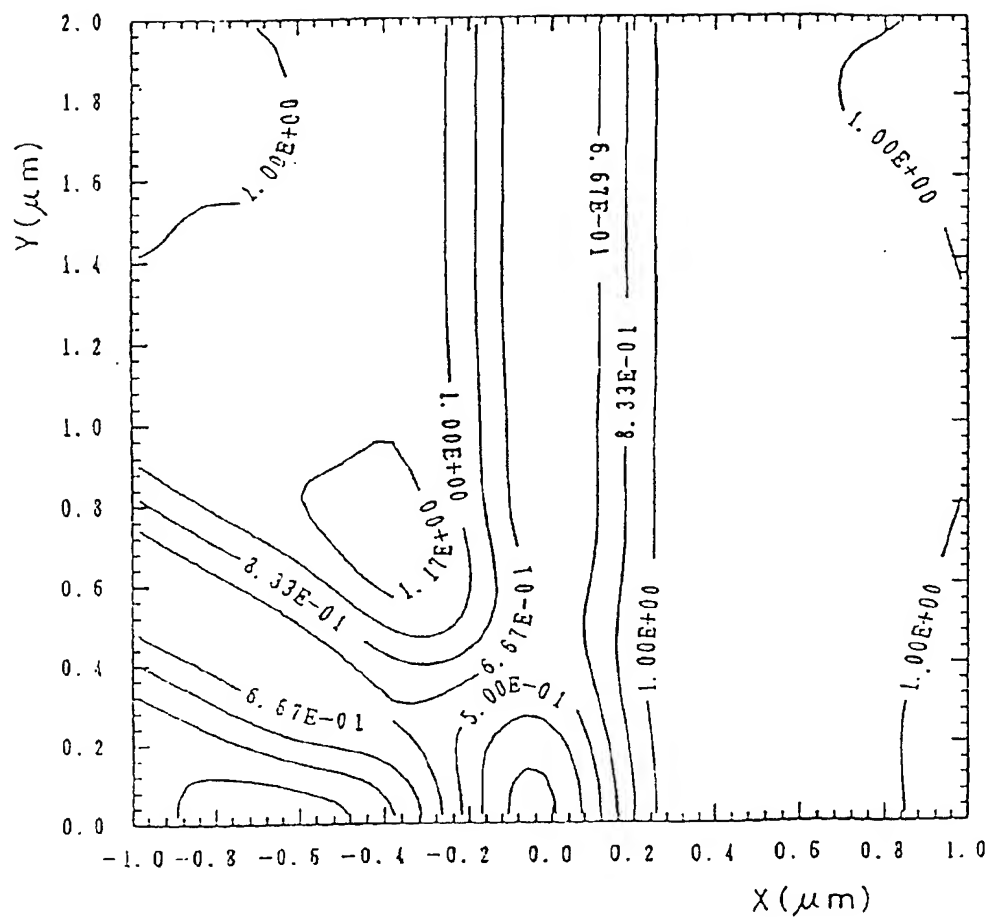


FIG. 67 A

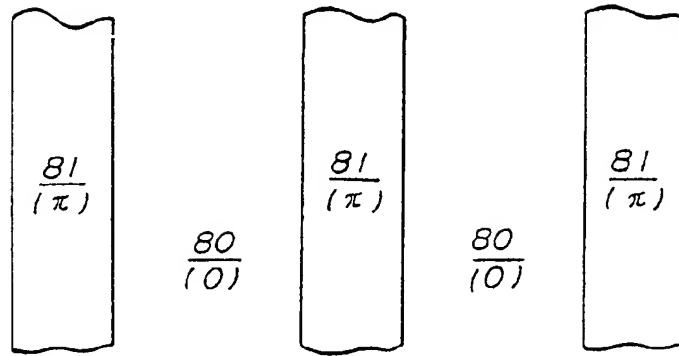


FIG. 67 B

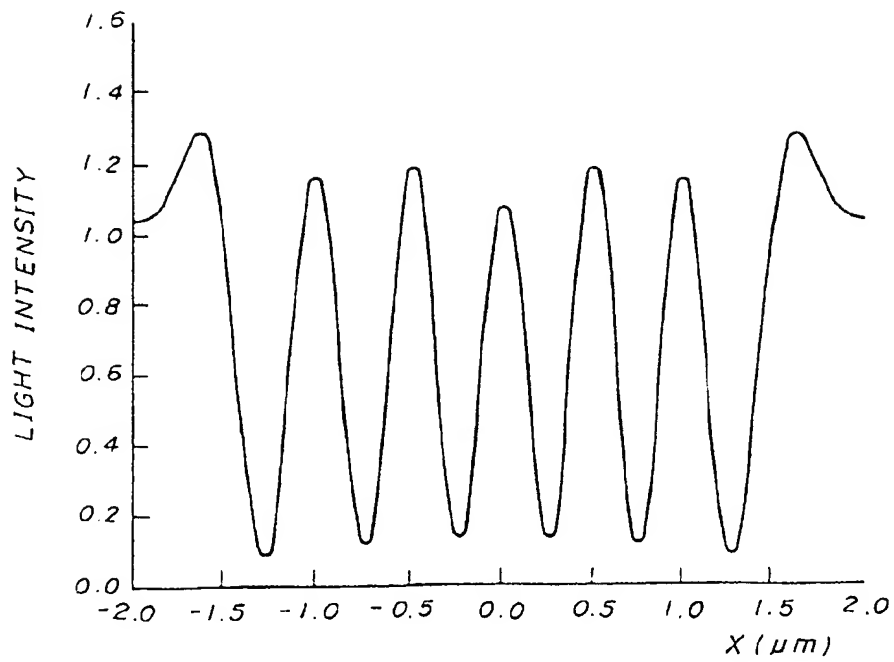


FIG. 68 A

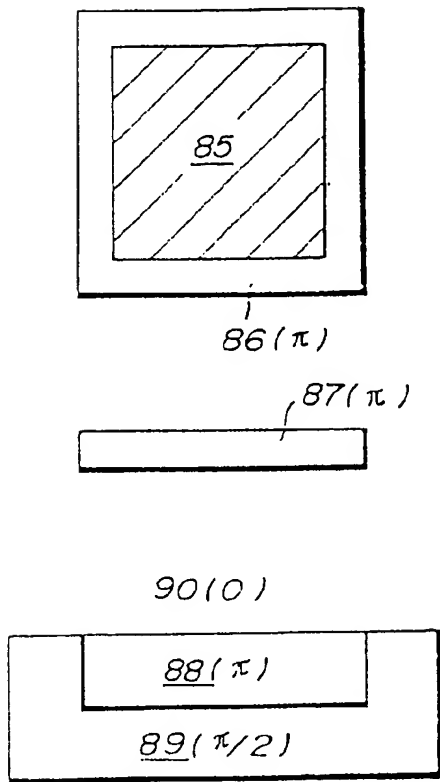


FIG. 68 B

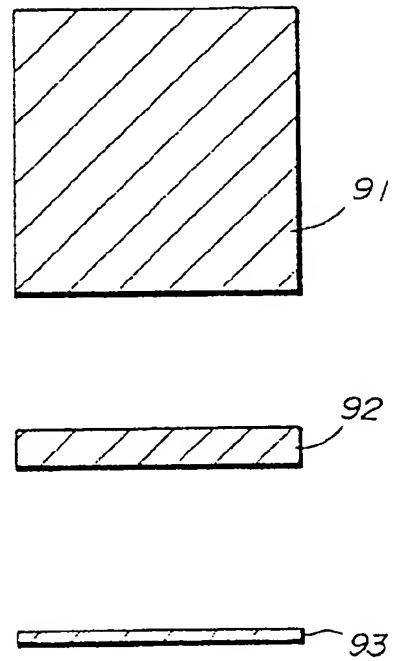


FIG. 69

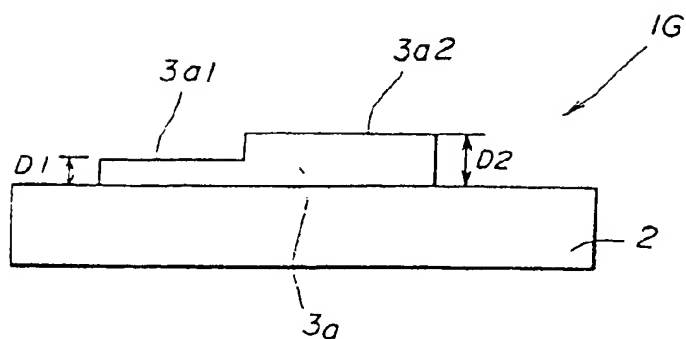


FIG. 70 C

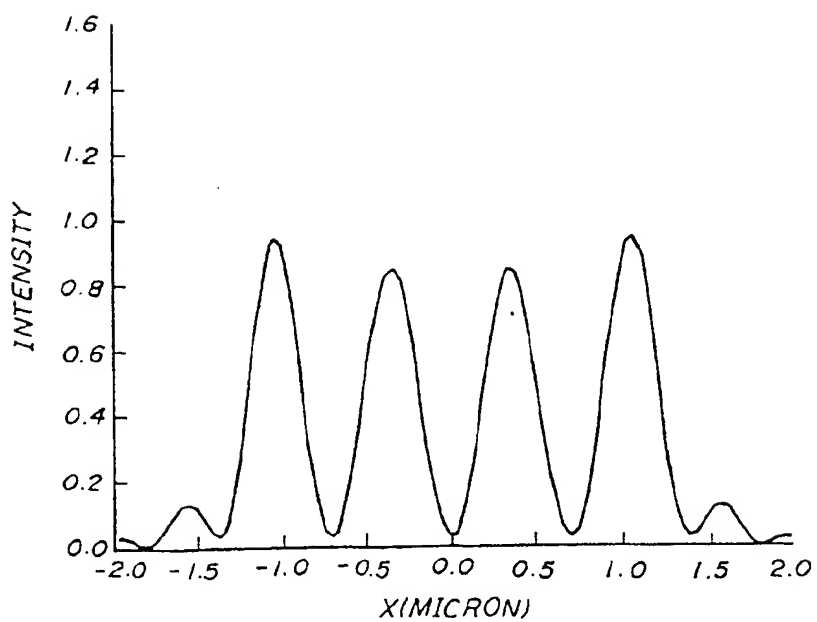


FIG. 70 A

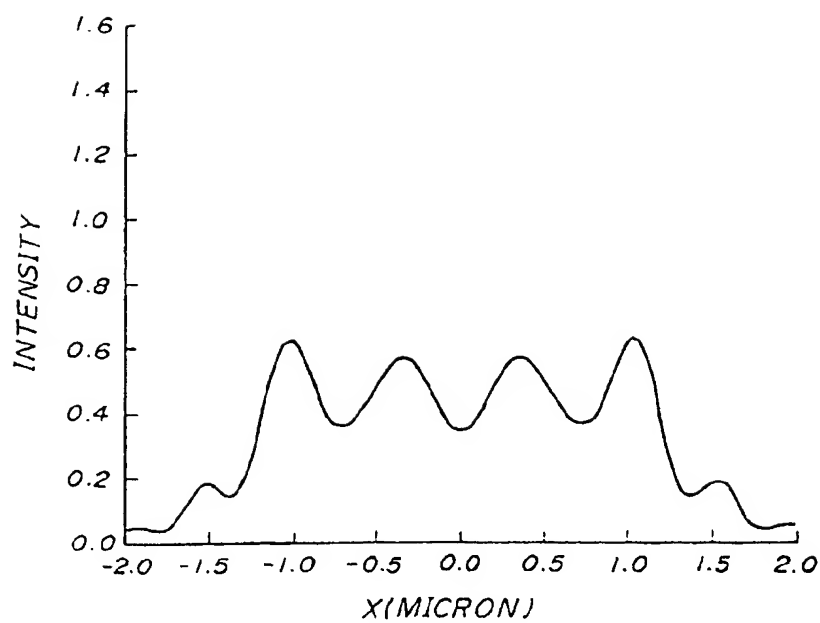


FIG. 70 B

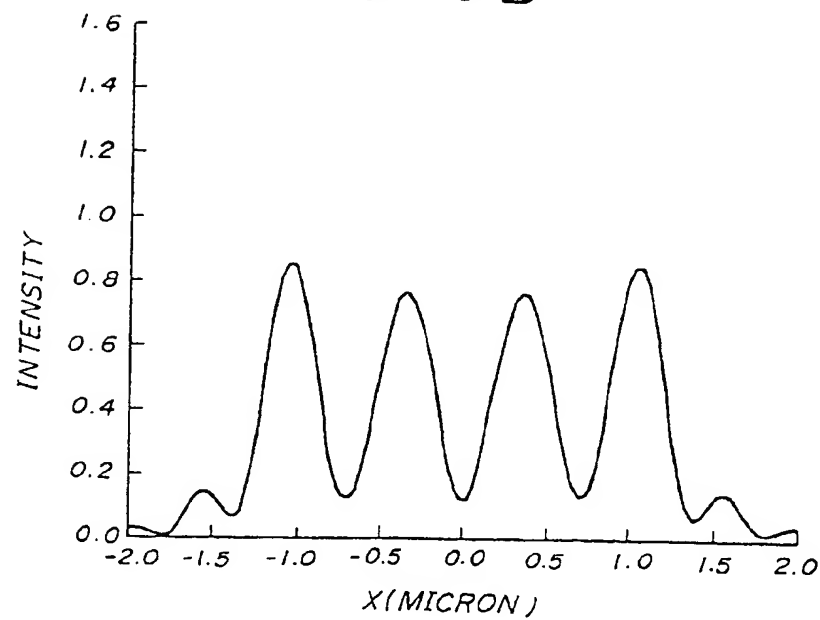




FIG. 70D

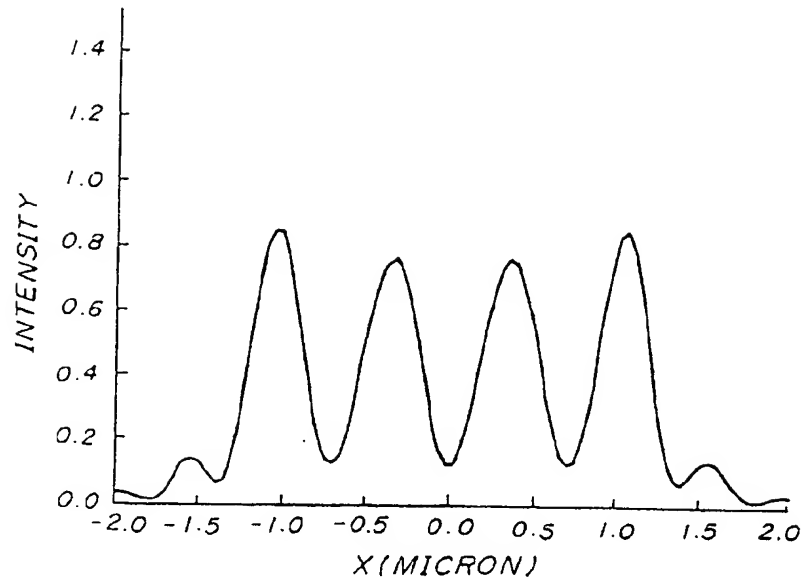


FIG. 70E

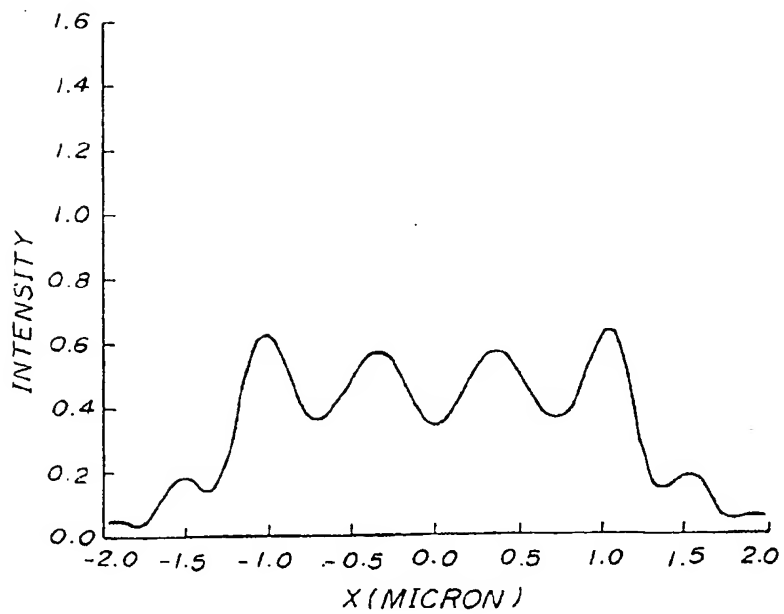


FIG. 71 A

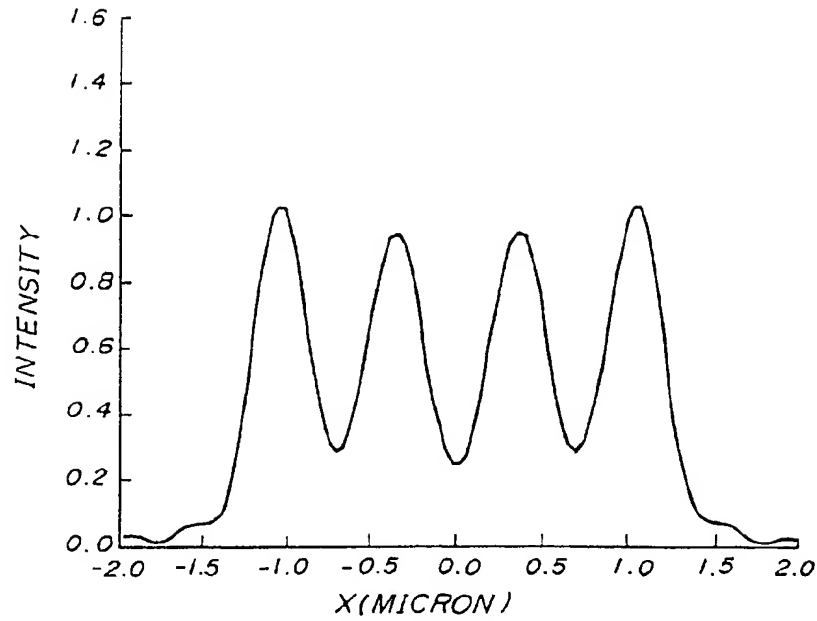


FIG. 71 B

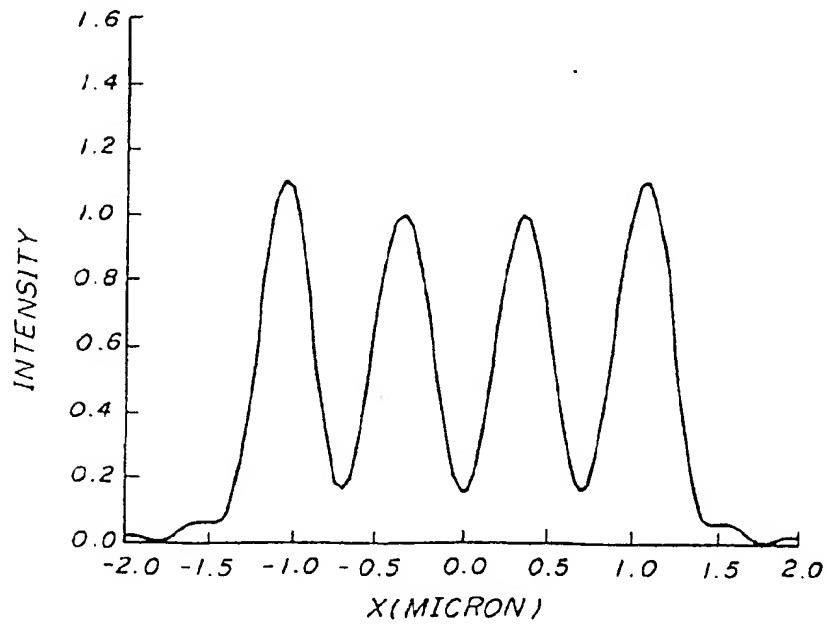


FIG. 71 C

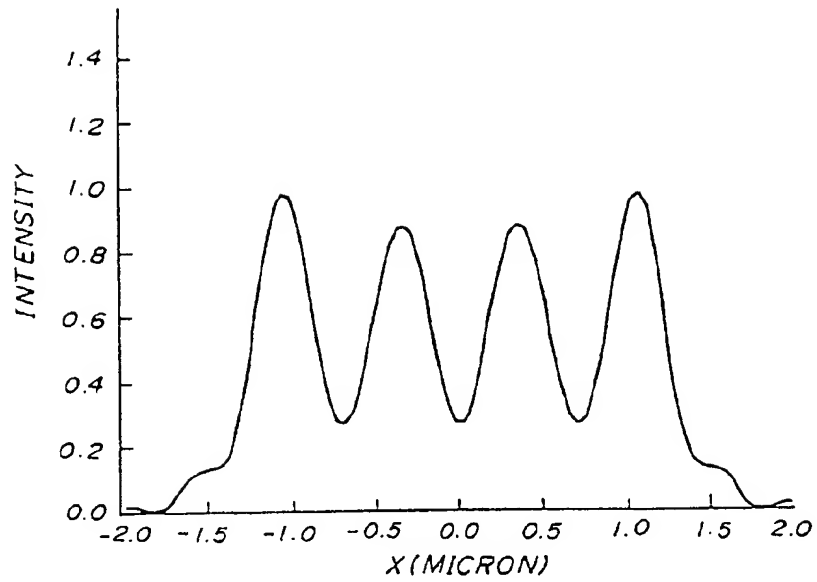


FIG. 71 D

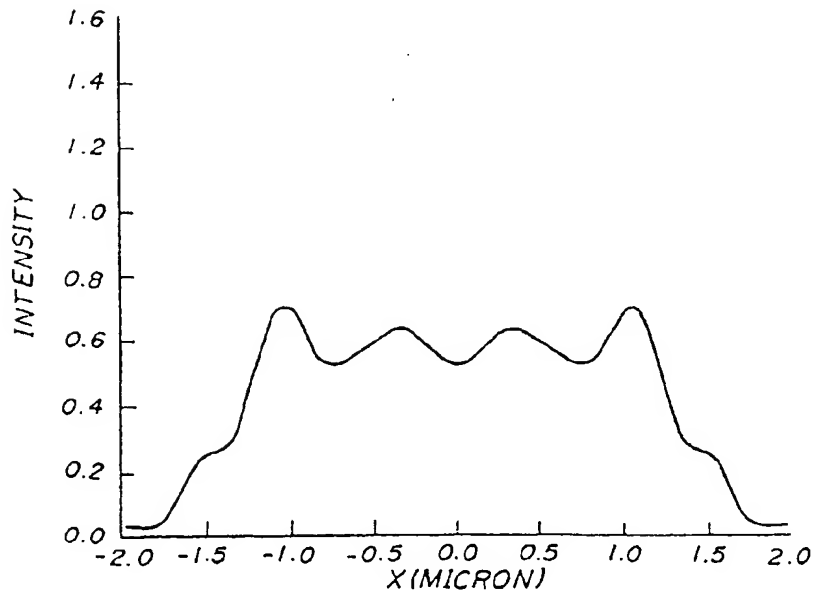


FIG. 72 A

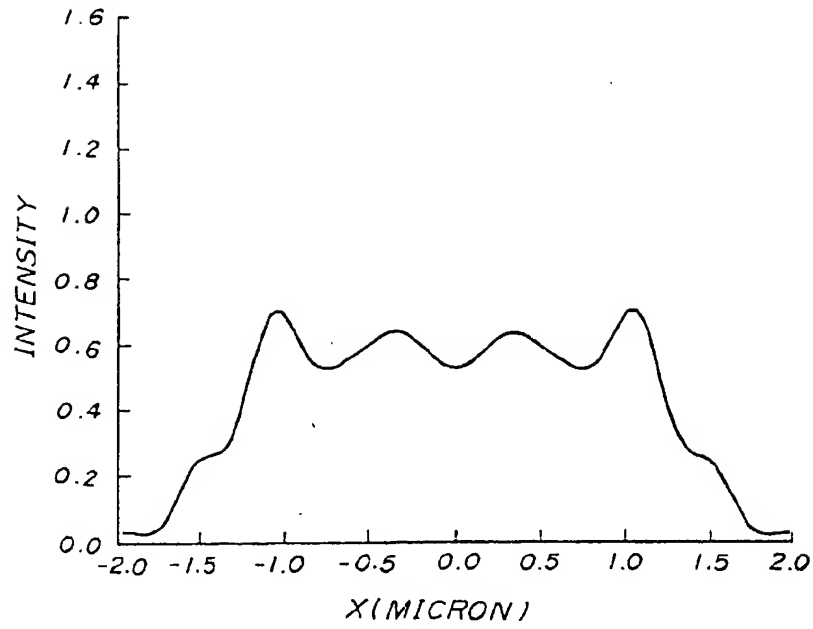


FIG. 72 B

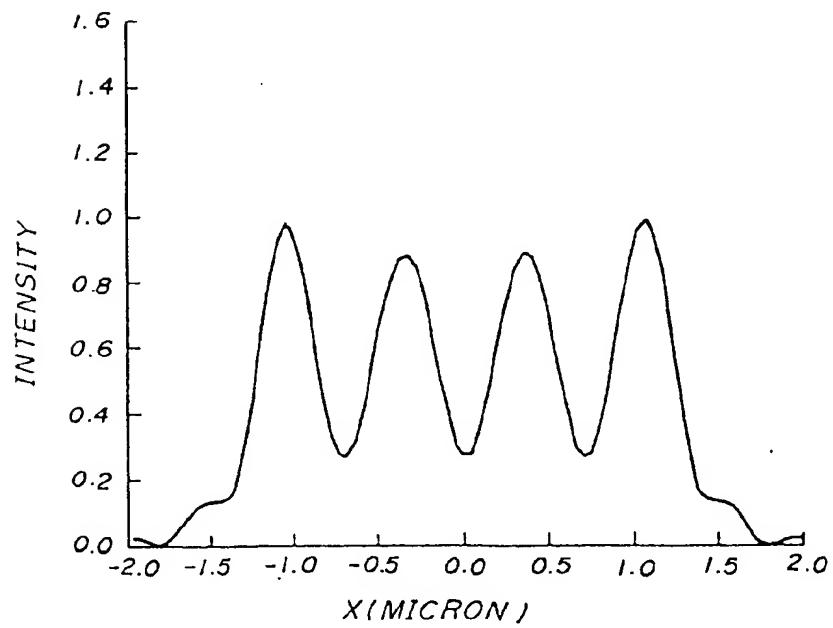


FIG. 72 C

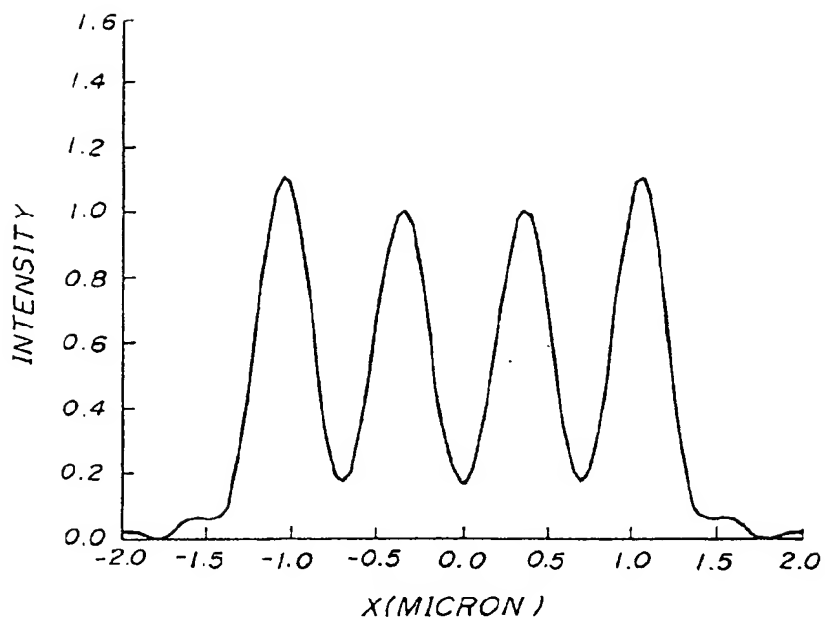


FIG. 72 D

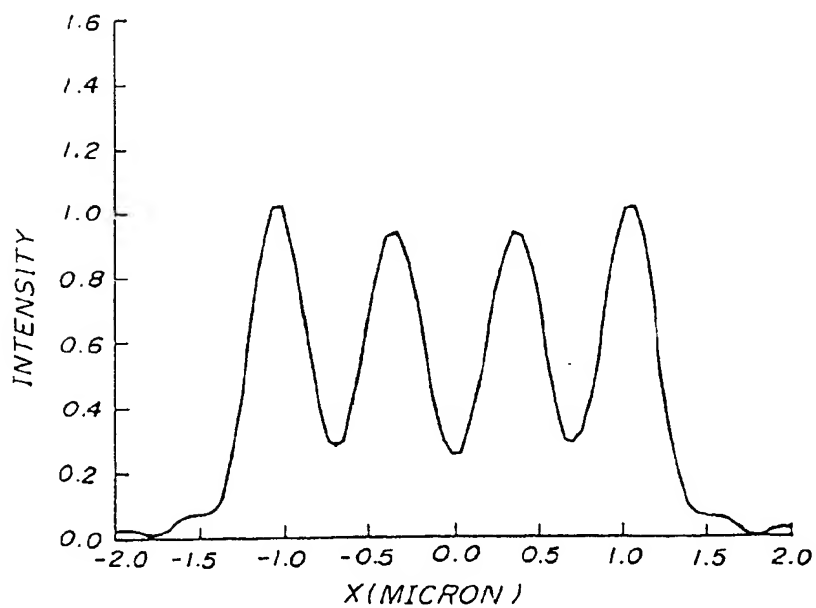


FIG. 73

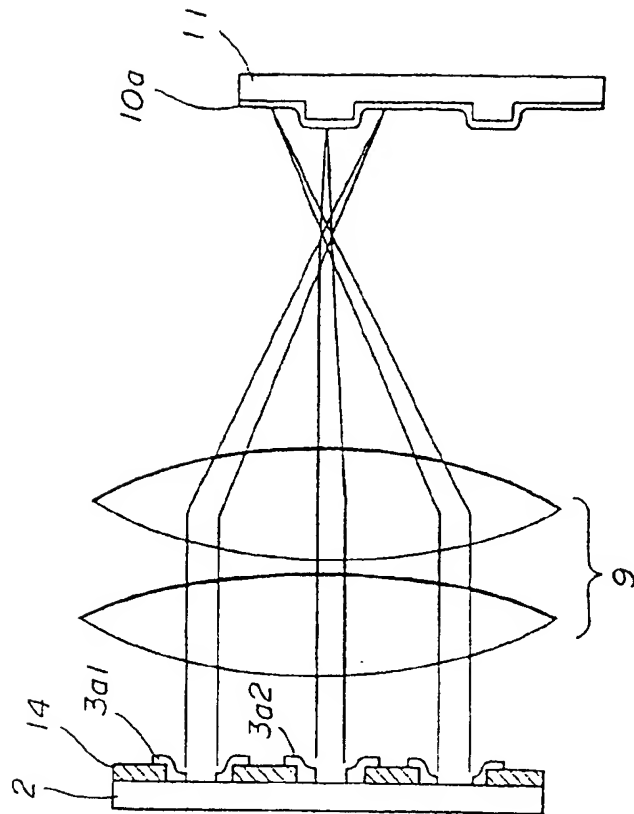


FIG.74 A

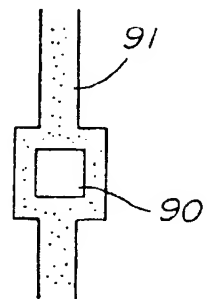


FIG.74 B



FIG.75 A

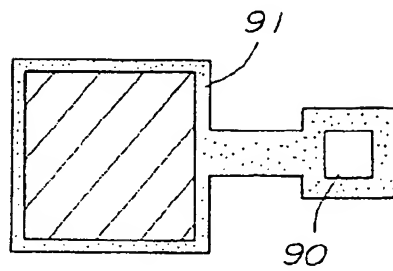


FIG.75 B

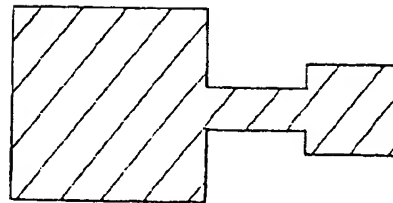


FIG. 76 A

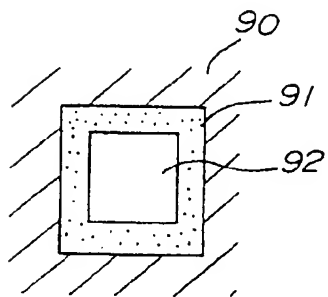


FIG. 76 B

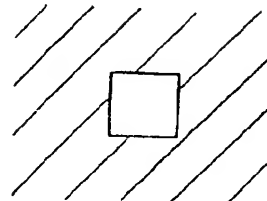


FIG. 77 A

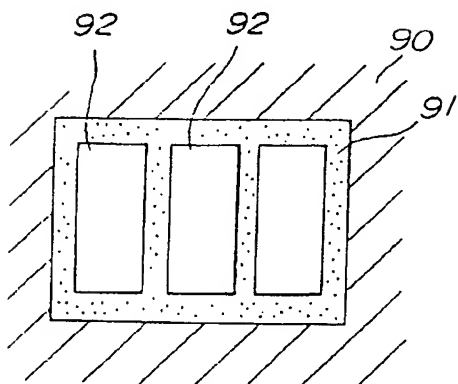
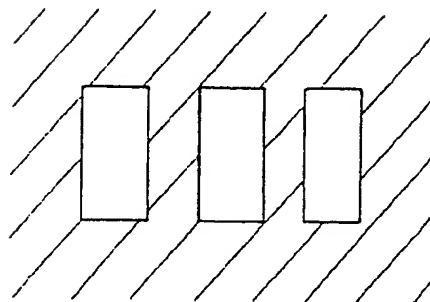


FIG. 77 B







Europäisches Patentamt  
European Patent Office  
Office européen des brevets



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(54) Mask, mask producing method and pattern forming method using mask

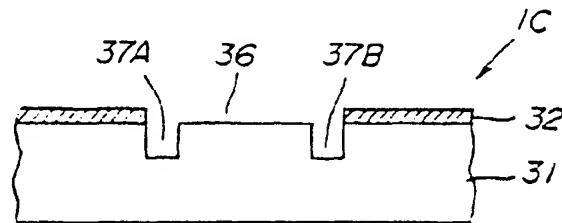
(57) A mask for use in exposure of a semiconductor wafer includes transparent portions (2, 31, 51) for transmitting light used in the exposure, formed by a transparent layer and corresponding to first areas of the wafer, these being areas which are to be exposed, opaque portions (14, 32, 53) for masking the light, formed by an opaque layer and corresponding

to second areas of the wafer adjacent to the first areas, and phase shift portions (3a, 37A, 37B, 41A, 41B) for shifting the phase of the light so as to improve the contrast between the first and second areas, formed by a phase shift layer (3a) formed over the transparent layer and the opaque layer. According to the invention, in at least one part of the

mask the phase shift portions are formed only along edges of the opaque portions (14, 32, 53) without extending between adjacent opaque portions. A

method of producing such a mask, and a pattern forming method employing the mask, are also disclosed.

FIG. 46E





European Patent  
Office

# EUROPEAN SEARCH REPORT

Application Number  
EP 95 10 1229

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claims	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
E	EP-A-0 383 534 (TOKYO SHIBAURA ELECTRIC CO) * the whole document *	1	G03F1/14
A	EP-A-0 090 924 (IBM) 12 October 1983 * the whole document *	1	
E	EP-A-0 234 547 (SHARP KK) 2 September 1987 * the whole document *	1	
			TECHNICAL FIELDS SEARCHED (Int.Cl.5)
			G03F
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 13 October 1995	Examiner Rasschaert, A
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application I : document cited for other reasons & : member of the same patent family, corresponding document	

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